Gravitational Waves: a New Window onto the Universe

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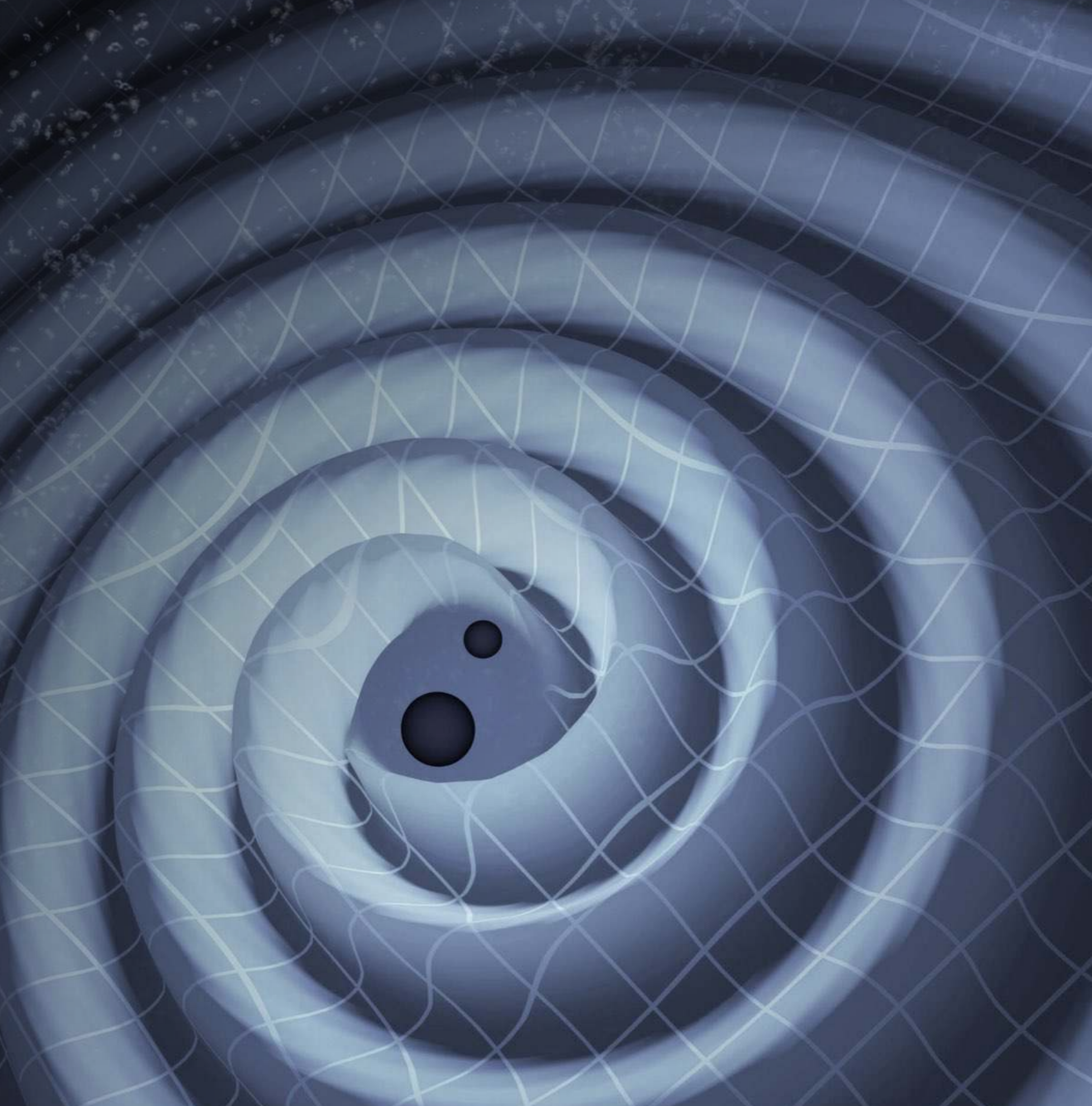
ISAPP @ Pierre Auger
March 4, 2019



PART I.a

what are gravitational waves?

general relativity

spacetime is dynamic!

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

curvature

stress

general relativity

spacetime is dynamic!

“*Spacetime tells matter how to move;*
matter tells spacetime how to curve”

John Wheeler


Image credit: LIGO/Caltech

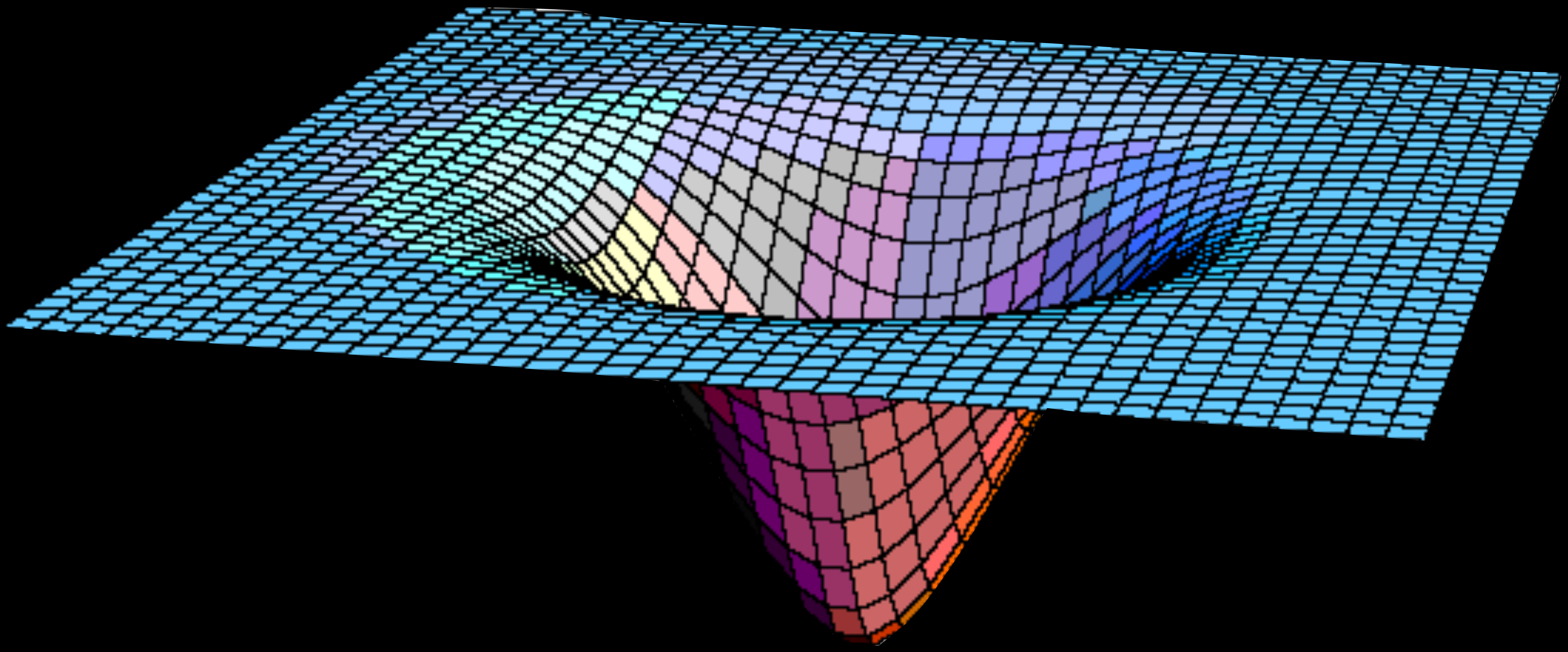
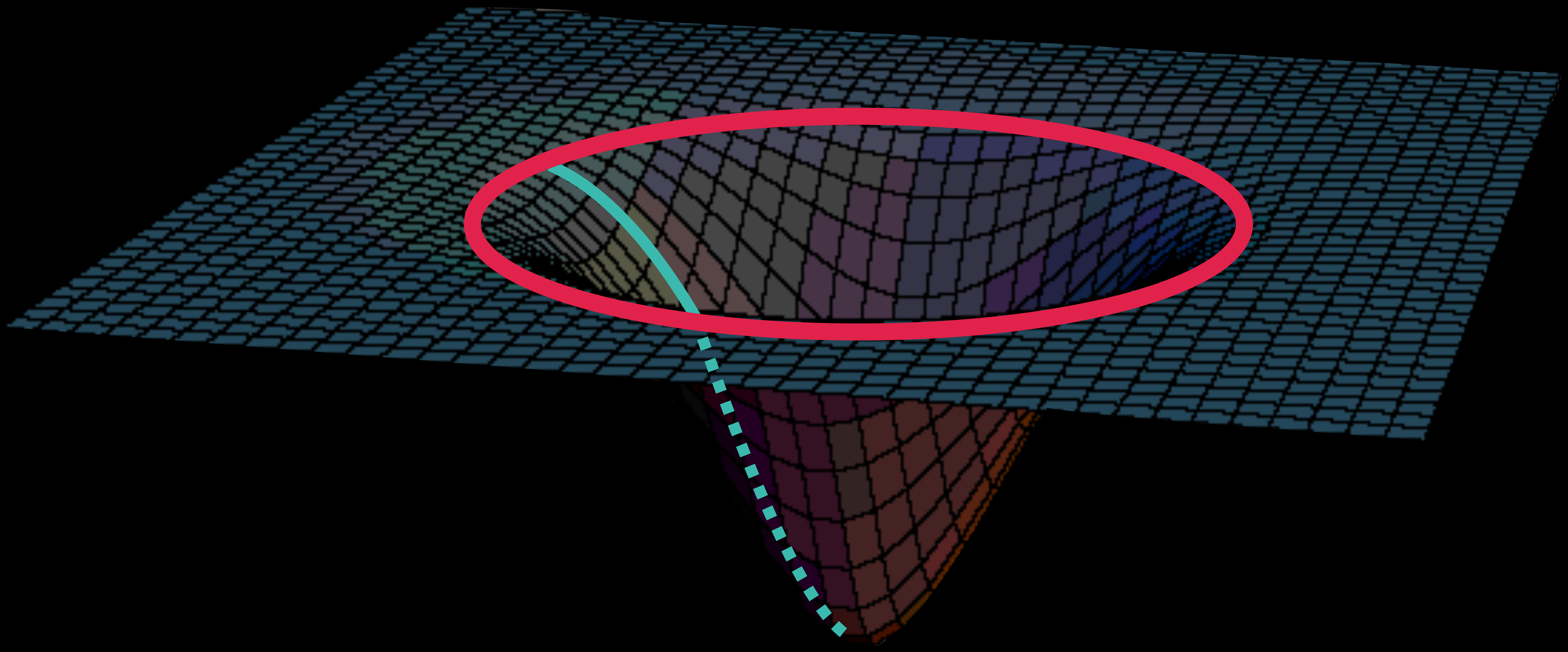


Image credit: U Toronto



circumference ≠ 2π radius

Image credit: U Toronto


Image credit: LIGO/Caltech


Video credit: LIGO/T. Pyle

what's the effect of a GW?

two points to consider

1.

equivalence principle

gravity couples universally to all mass-energy

hence we cannot detect a *constant* g-field

2.

tidal field

however, we can measure *variations* in the field

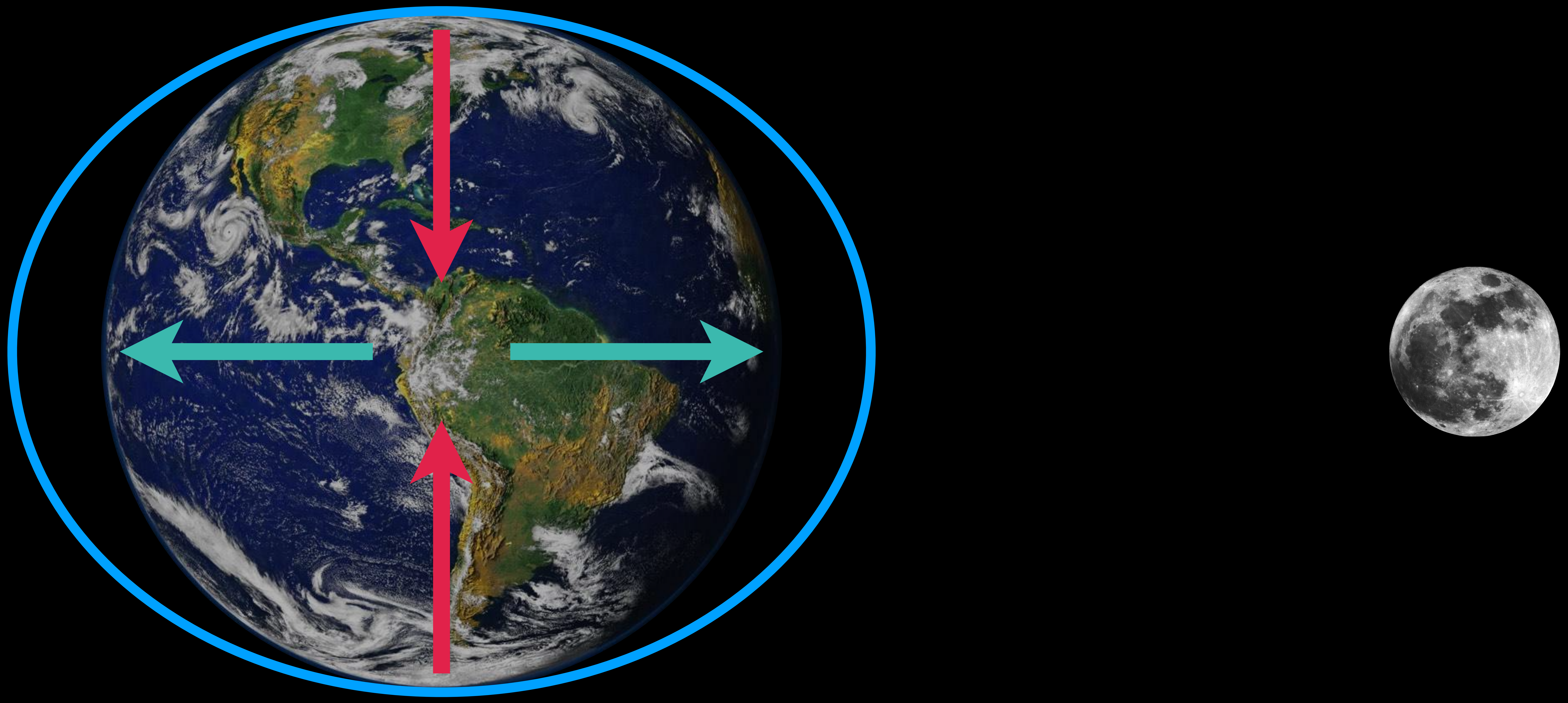
i.e. we can measure tidal forces (grad-g)

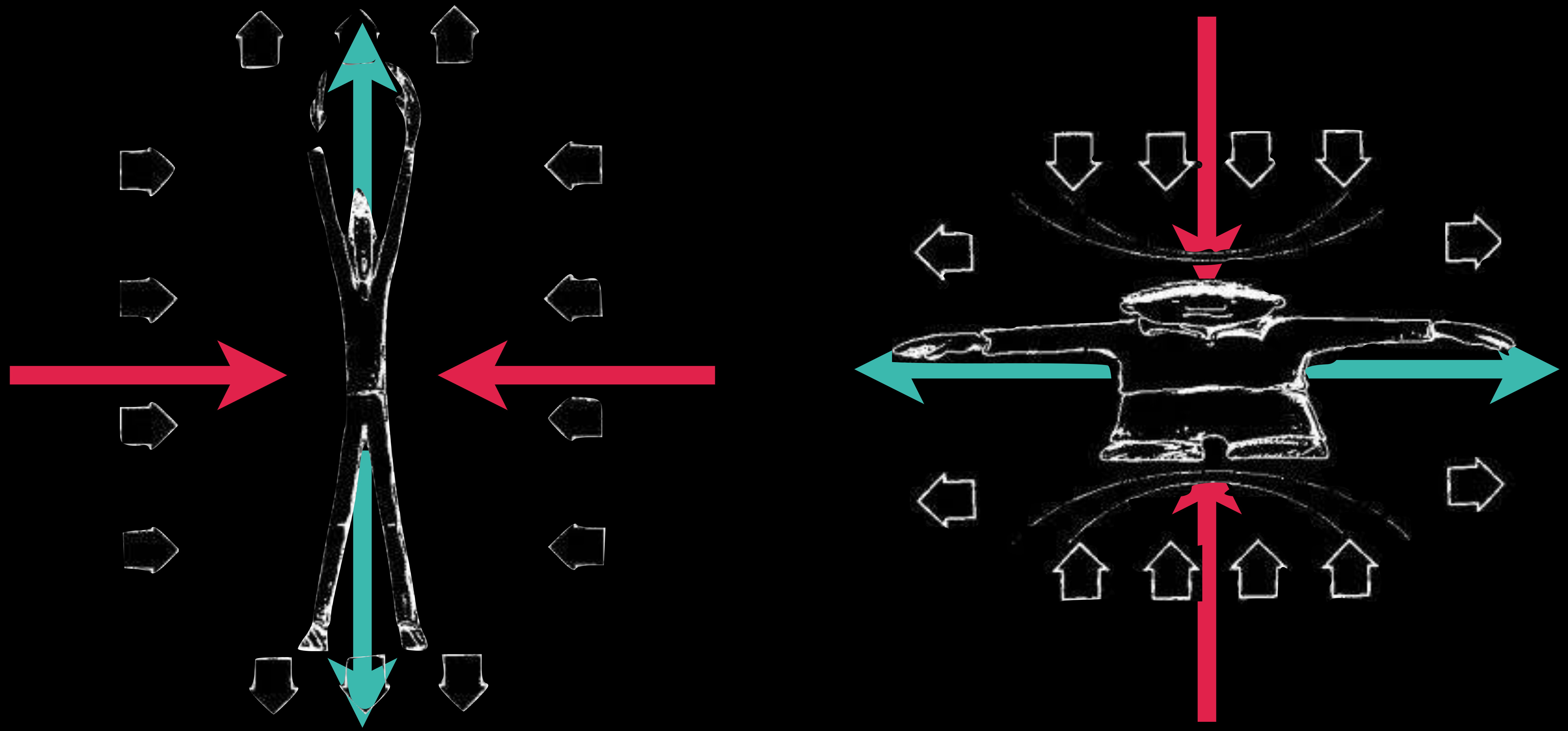
what’s the effect of a GW?

tidal forces

what's the effect of a GW?

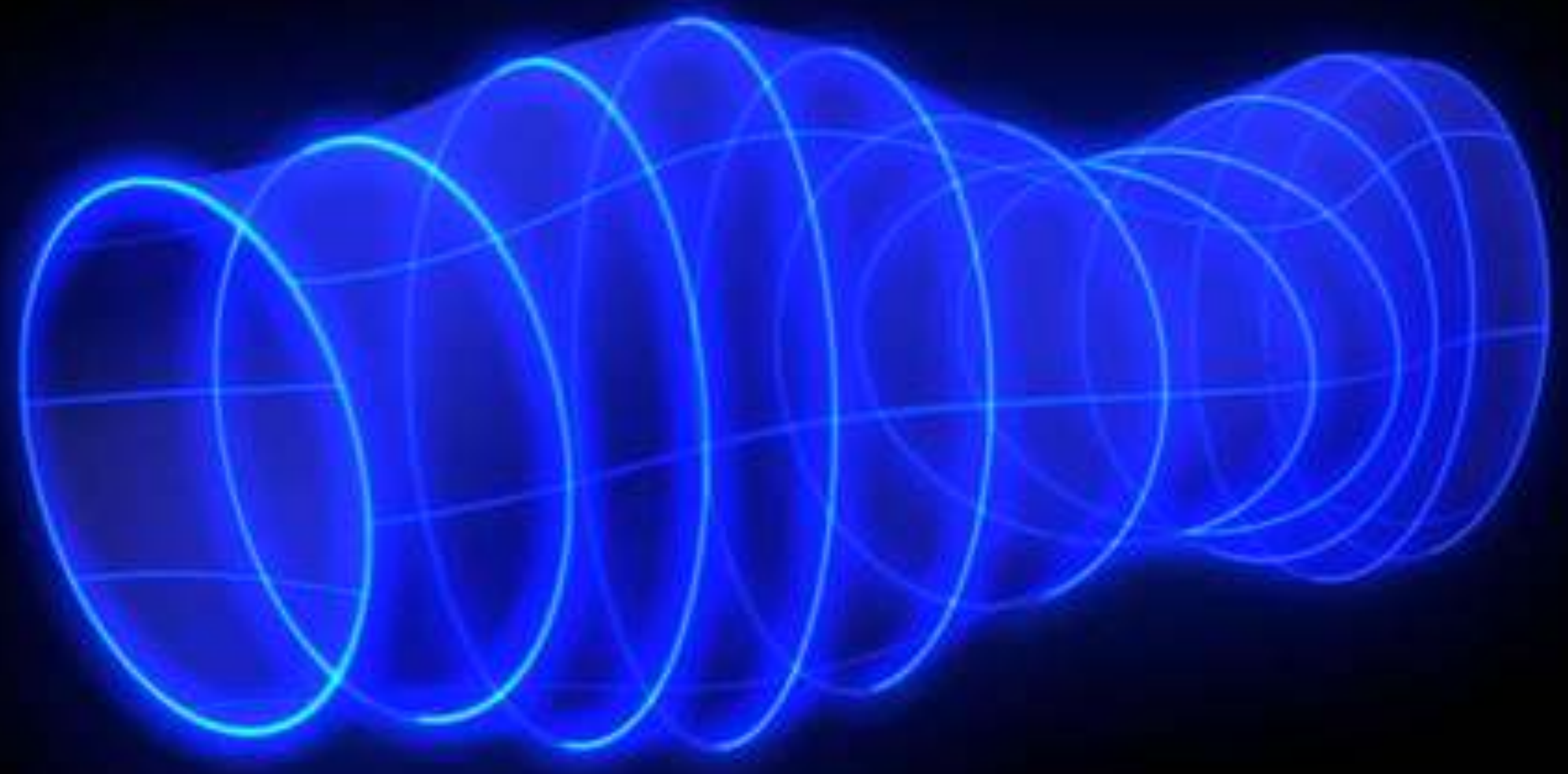
tidal forces





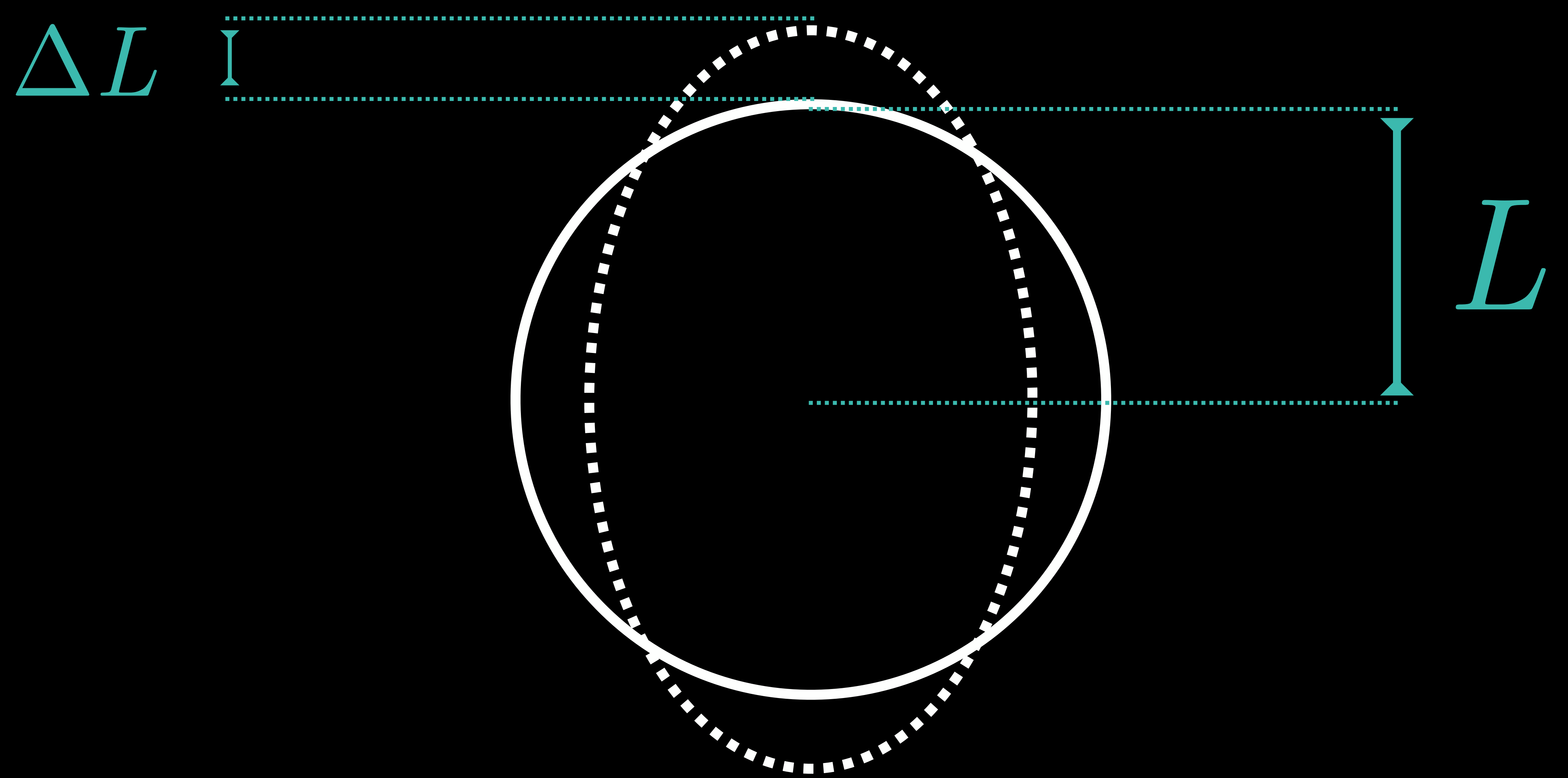
⊙ wave propagates out of the screen

Image credit: Auriga from the INFN in Italy.



wave propagates along cylinder

strain



$$h \stackrel{\text{def}}{=} \frac{\Delta L}{L}$$

PART 1.b
how are GWs generated?

general relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

how are GWs generated?

an analogy

electromagnetic field

want a time-varying source that produces a $\sim 1/r$ radiative field

⊕ **monopole doesn't work** ⟶ $E_{\rm mon} \sim \frac{Q}{r^2}, \frac{\dot{Q}}{r}$ charge conserved

⊕ ⊖ **dipole does work** ⟶ $E_{\rm dip} \sim \frac{P}{r^3}, \frac{\dot{P}}{r^2}, \frac{\ddot{P}}{r}$

here r is the distance to the observer

Pedagogy credit: T. Creighton

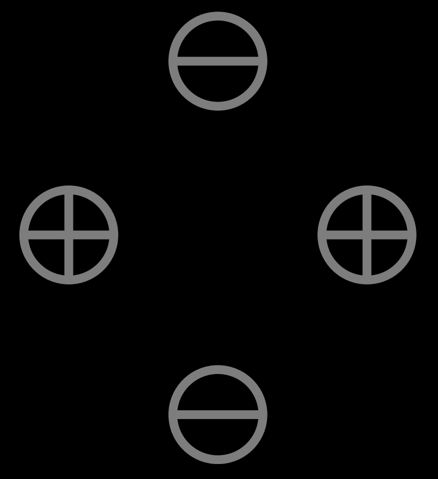
how are GWs generated?

gravitational tidal field

want a time-varying source that produces a $\sim 1/r$ radiative field

monopole doesn't work ⟶ $g'_{\text{mon}} \sim \frac{M}{r^3}, \frac{\dot{M}}{r^2}$ mass conserved

dipole doesn't work ⟶ $g'_{\text{dip}} \sim \frac{P}{r^4}, \frac{\dot{P}}{r^3}, \frac{\ddot{P}}{r^2}$ momentum conserved

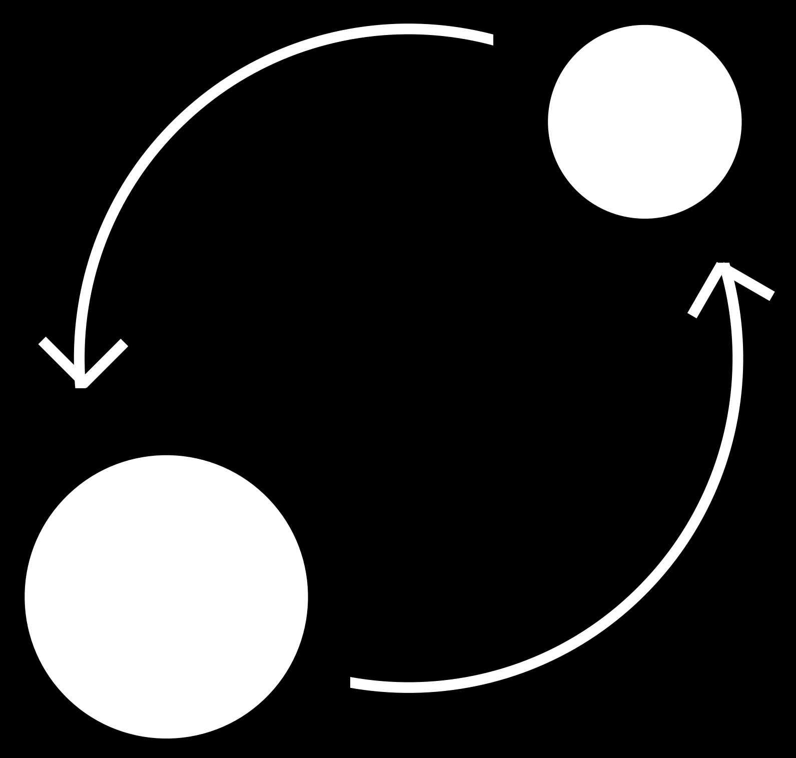


quadrupole does work ⟶ $g'_{\text{quad}} \sim \frac{I}{r^5}, \frac{\dot{I}}{r^4}, \frac{\ddot{I}}{r^3}, \frac{\dddot{I}}{r^2}, \frac{\ddddot{I}}{r}$

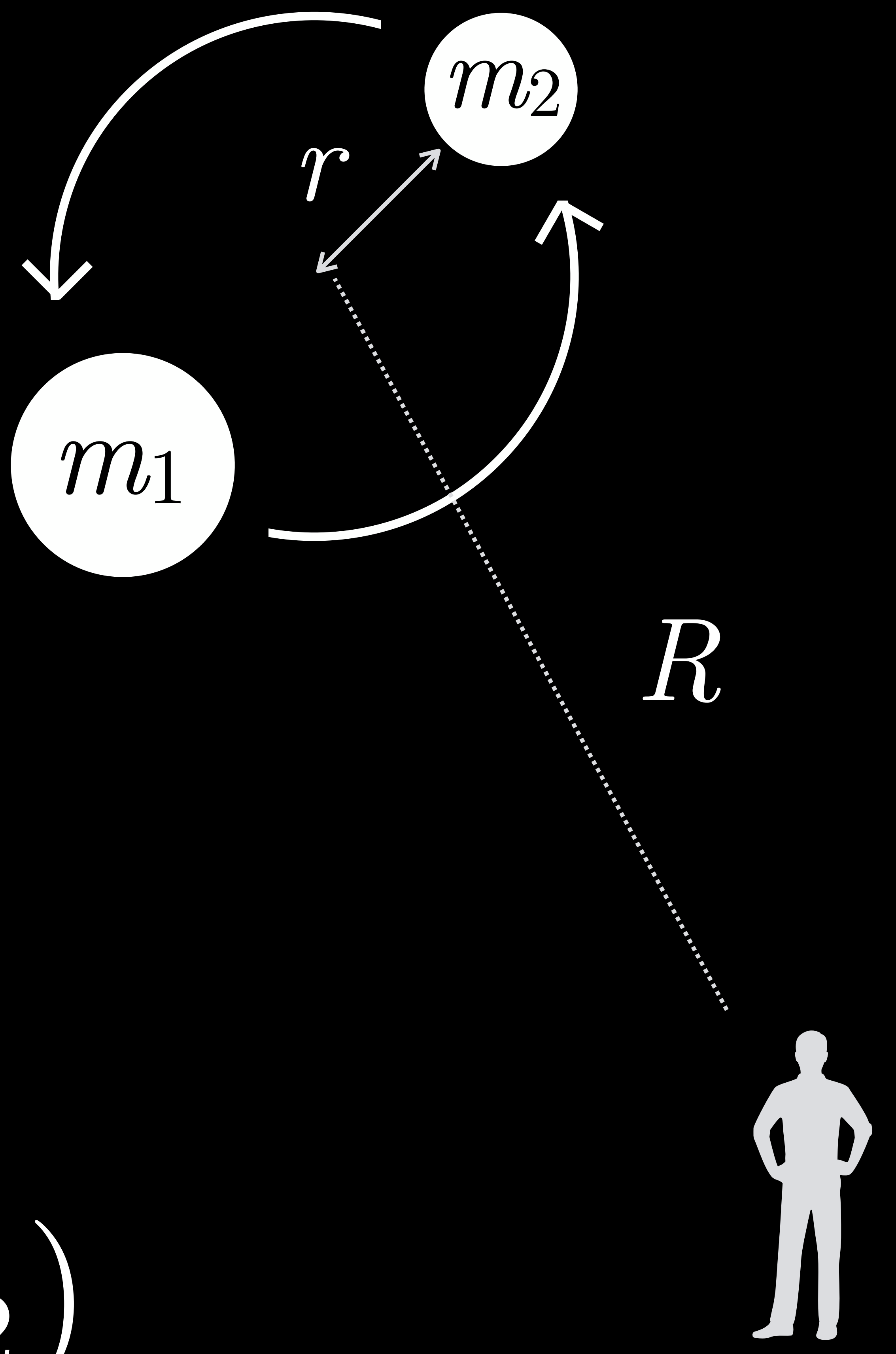
here r is the distance to the observer

Pedagogy credit: T. Creighton

binary system



binary system



strain

$$|h| \propto \frac{1}{R}\frac{m_1 m_2}{r}$$

radiated power

$$\dot{E}_{\mathrm{GW}} \propto -\frac{(m_1 m_2)^2 (m_1 + m_2)}{r^5}$$

more mass
closer together → more GWs!

binary system
an example

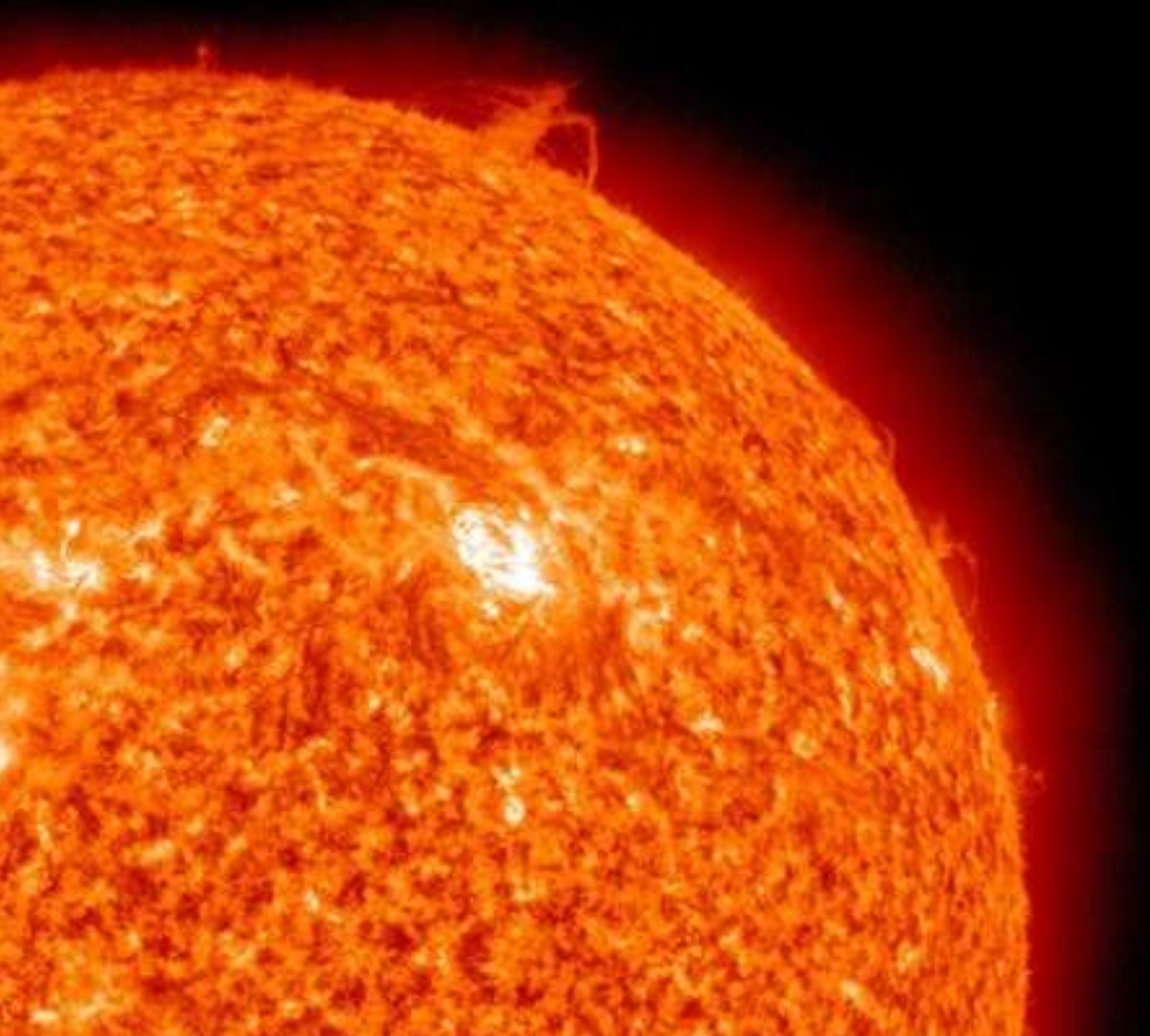
$$|h| \sim 10^{-26}$$

strain one light-year away

$$|\dot{E}_{\mathrm{GW}}| \sim 200\ \mathrm{W}$$

power emitted in GWs

very weak!



general relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

general relativity

$$\text{curvature} = (2 \times 10^{-43})\ \text{stress}$$

spacetime is very hard to bend!

(in SI units)

PART II.a

the detectors

(LIGO & Virgo)

LIGO

Laser **I**nterferometer **G**ravitational-wave **O**bservatory

Image credit: K. Staats

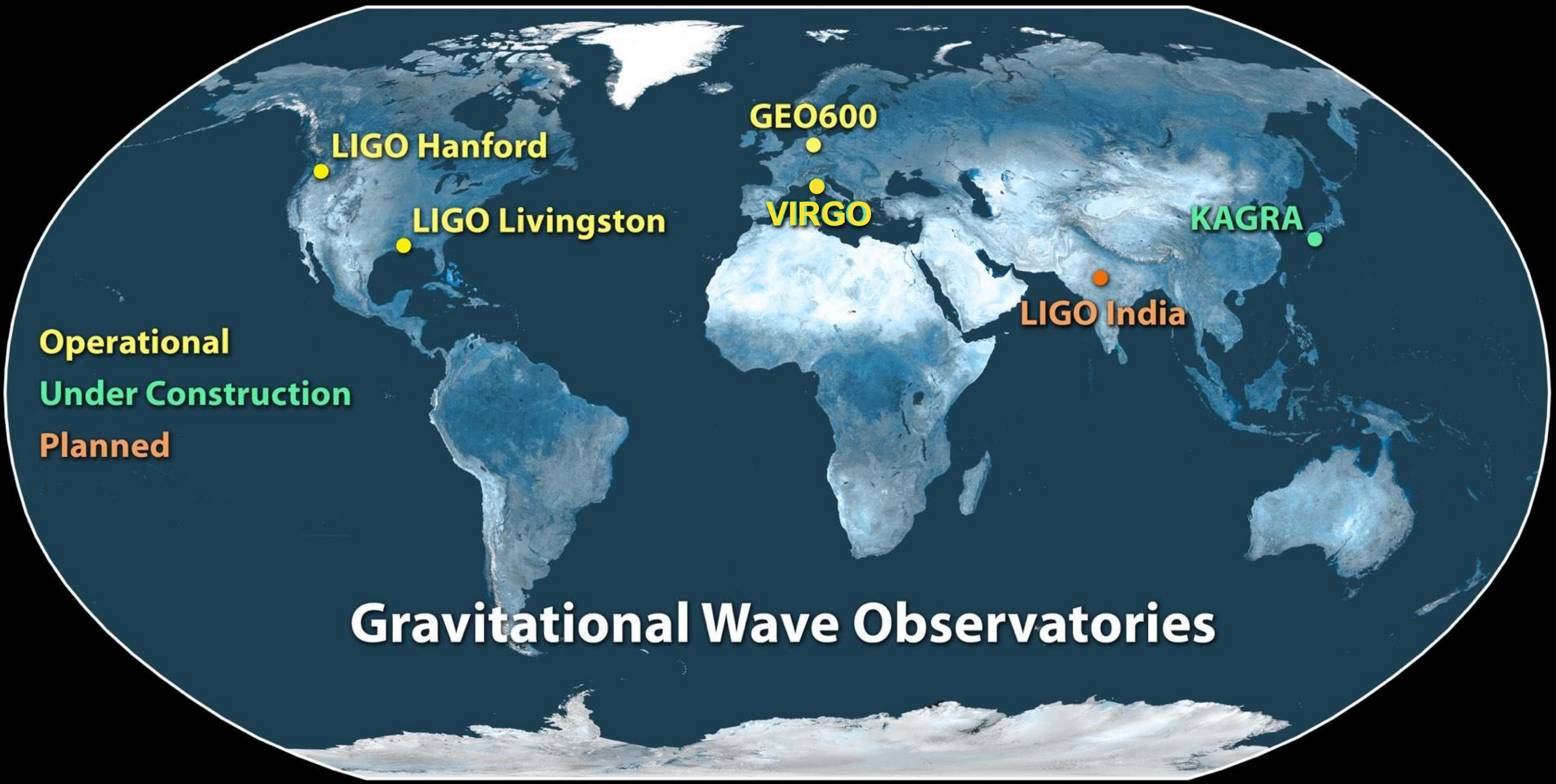


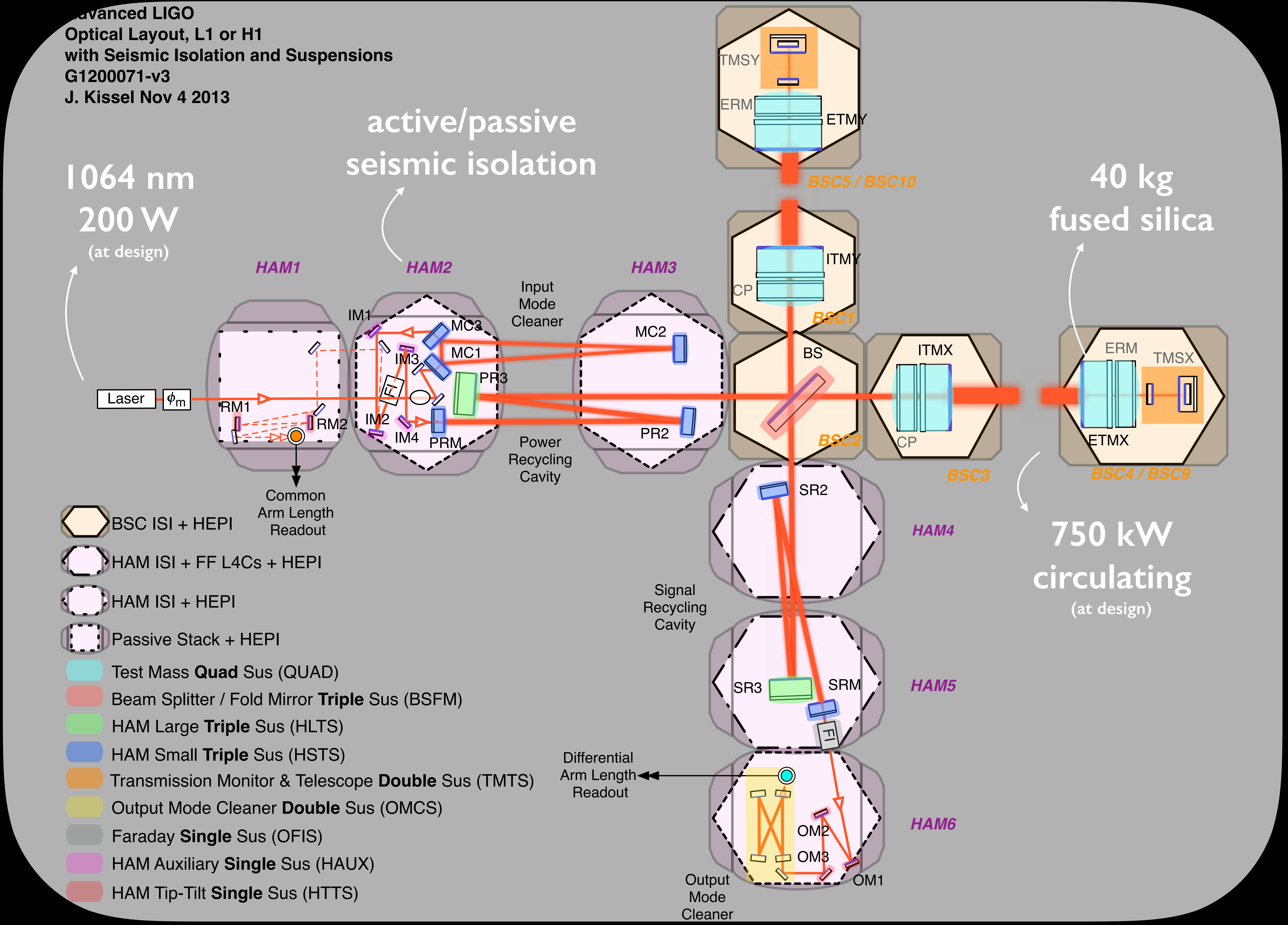
Image credit: LIGO

LIGO-Virgo Collaboration


Greenland
Iceland
Finland
Sweden
Norway
Russia
Canada
Germany
Ukraine
Kazakhstan
Mongolia
Spain
Turkey
China
Japan
North Atlantic Ocean
Iraq
Iran
Afghanistan
Algeria
Libya
Egypt
Saudi Arabia
Mexico
Thailand
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DR Congo
Indonesia
Tanzania
Papua New Guinea
Brazil
Peru
Angola
Bolivia
Namibia
Madagascar
Indian Ocean
Botswana
South Pacific Ocean
South Atlantic Ocean
Chile
South Africa
New Zealand
Argentina

Source


Video credit: LIGO/T. Pyle



dvanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013
active/passive
seismic isolation
1064 nm
200 W
(at design)
40 kg
fused silica
750 kW
circulating
(at design)
HAM1
HAM2
HAM3
HAM4
HAM5
HAM6
BSC5 / BSC10
BSC1
BSC2
BSC3
BSC4 / BSC9
TMSY
ERM
ETMY
ITMY
CP
BS
ITMX
CP
ERM
TMSX
ETMX
Laser
ϕ_m
RM1
RM2
IM1
IM2
IM3
IM4
MC1
MC2
MC3
PR2
PR3
PRM
FI
Input
Mode
Cleaner
Power
Recycling
Cavity
Common
Arm Length
Readout
SR2
SR3
SRM
FI
Signal
Recycling
Cavity
Differential
Arm Length
Readout
OM1
OM2
OM3
Output
Mode
Cleaner
BSC ISI + HEPI
HAM ISI + FF L4Cs + HEPI
HAM ISI + HEPI
Passive Stack + HEPI
Test Mass Quad Sus (QUAD)
Beam Splitter / Fold Mirror Triple Sus (BSFM)
HAM Large Triple Sus (HLTS)
HAM Small Triple Sus (HSTS)
Transmission Monitor & Telescope Double Sus (TMTS)
Output Mode Cleaner Double Sus (OMCS)
Faraday Single Sus (OFIS)
HAM Auxiliary Single Sus (HAUX)
HAM Tip-Tilt Single Sus (HTTS)

Video credit: K. Staats

Video credit: K. Staats

our bane: noise!

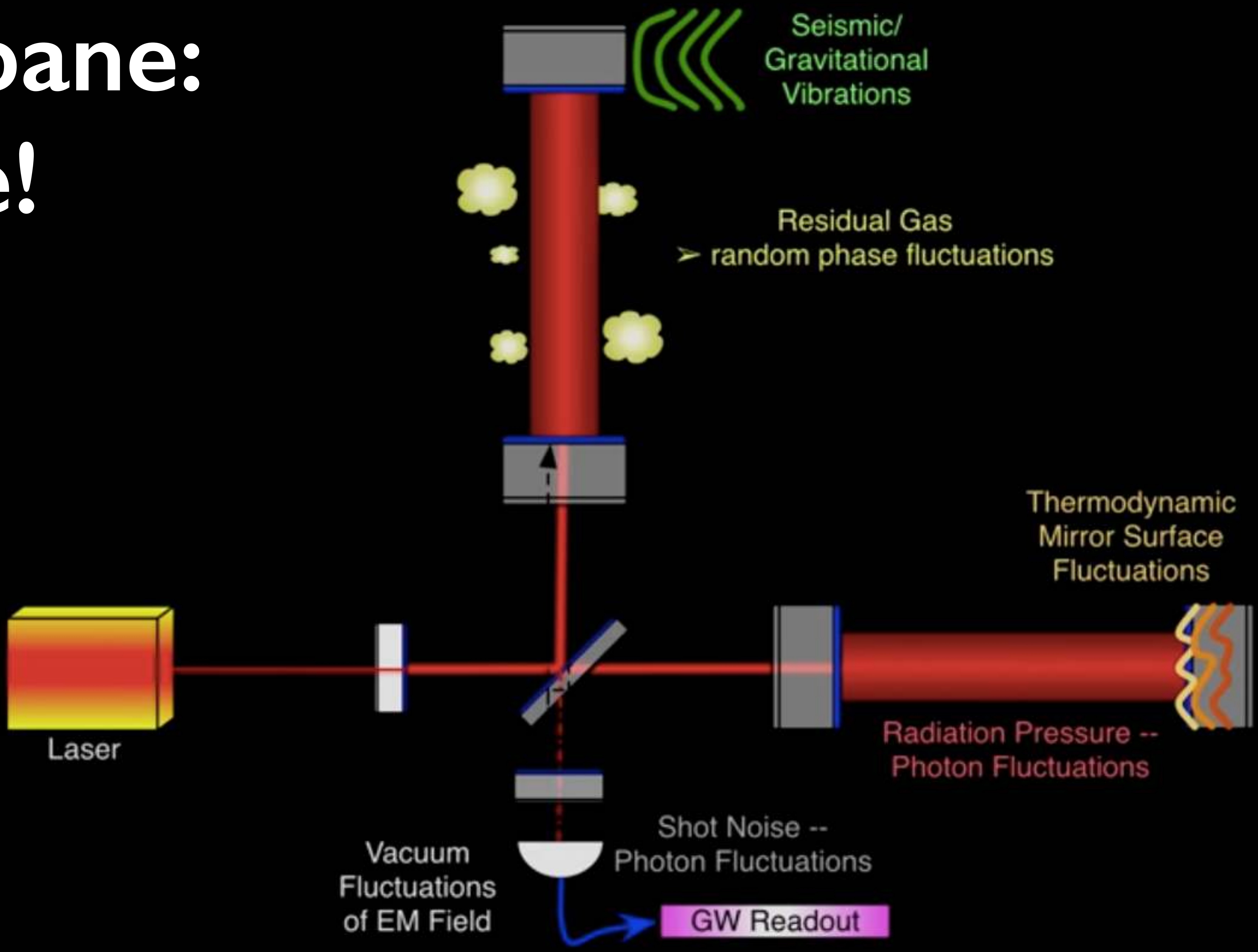


Image credit: R. Adhikari

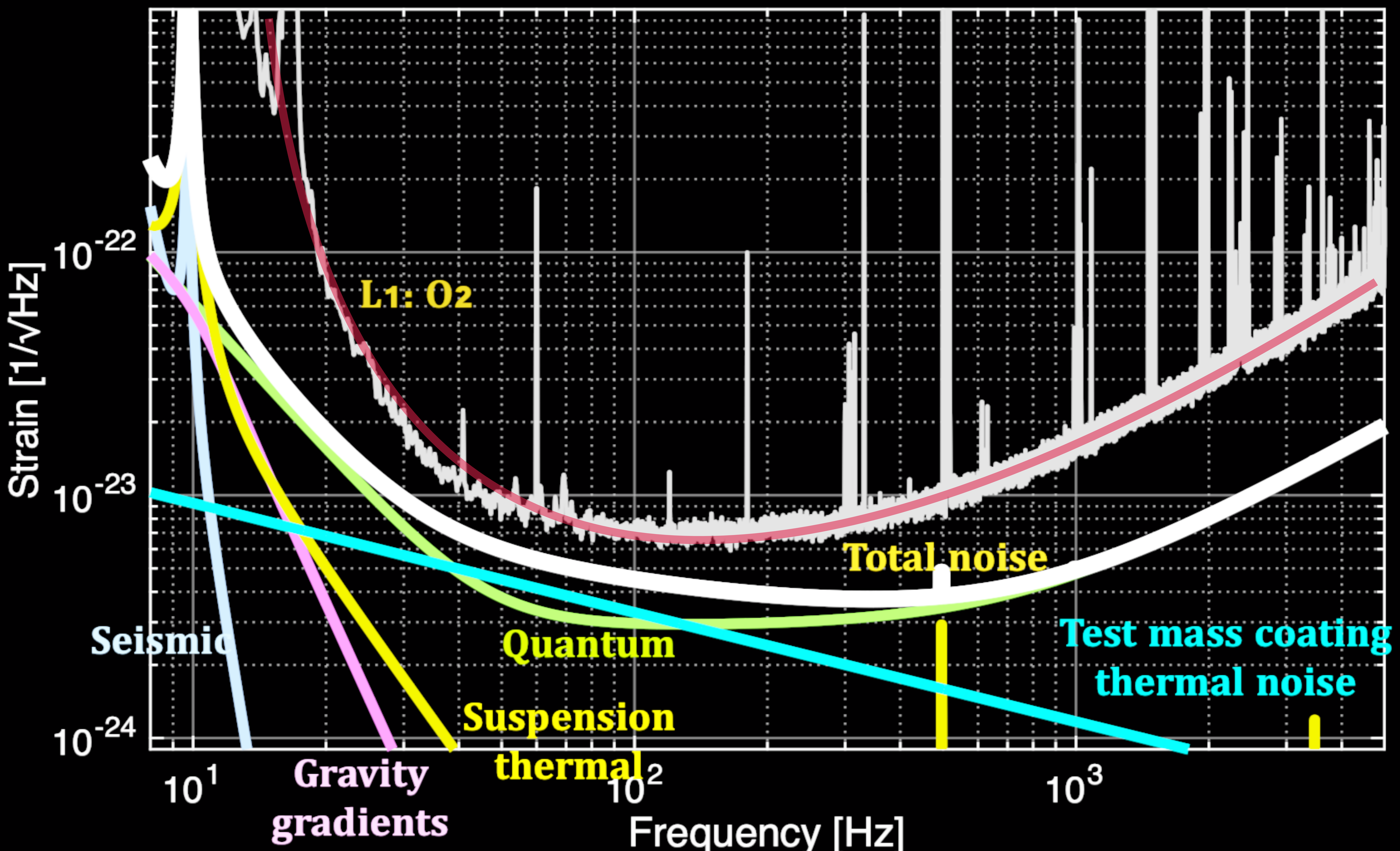
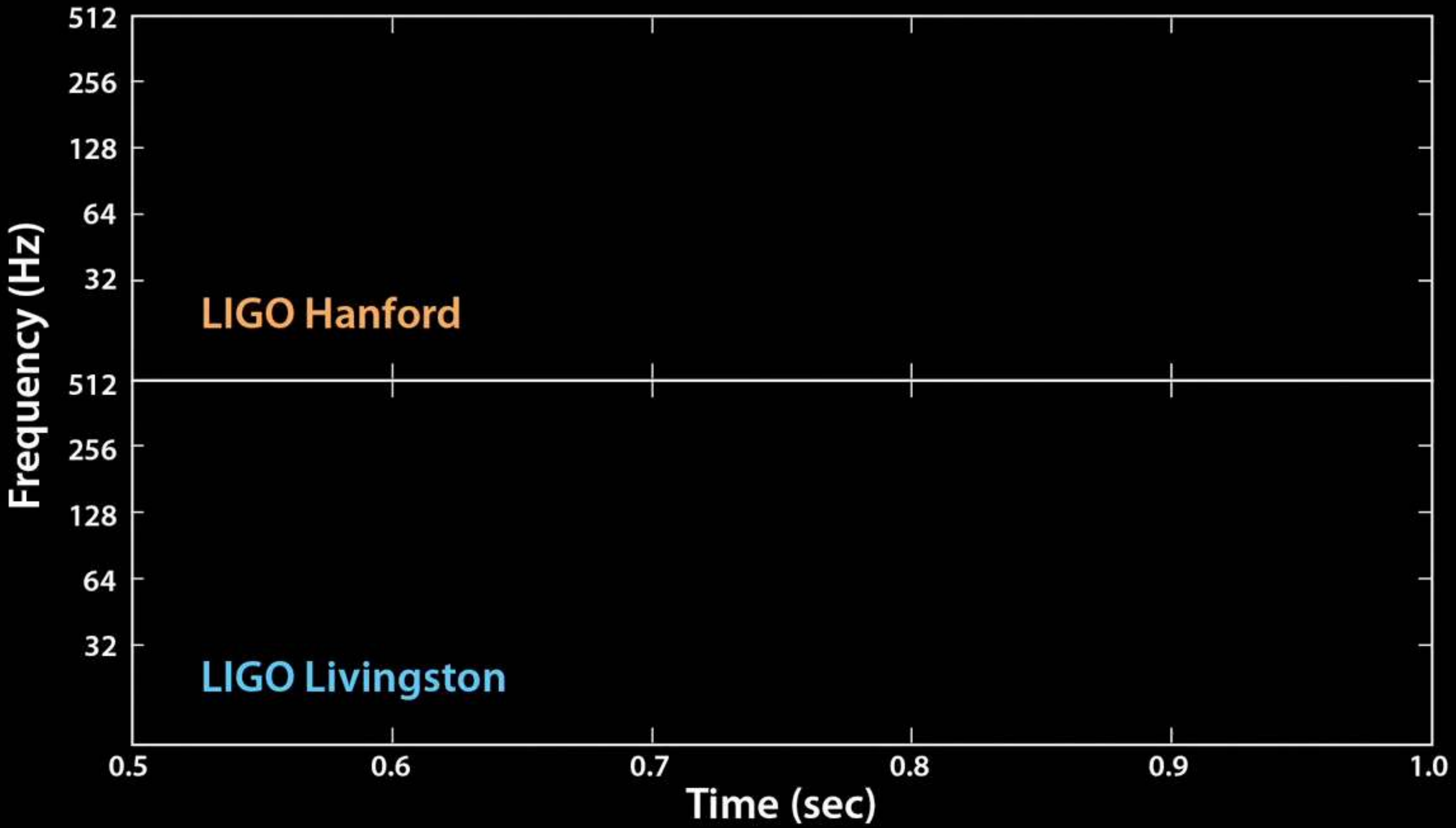


Image credit: LIGO/D. Shoemaker

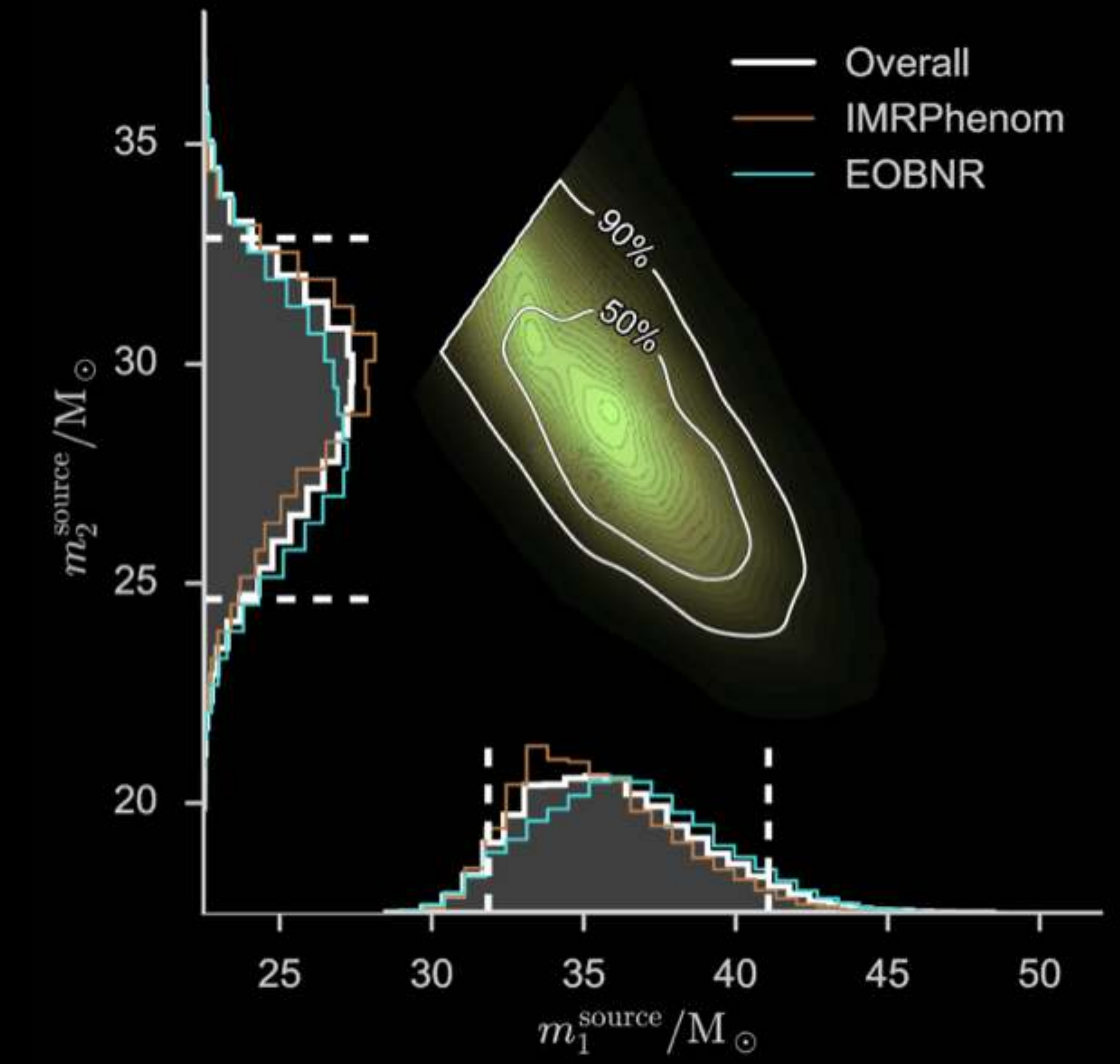
PART II.b
the detections

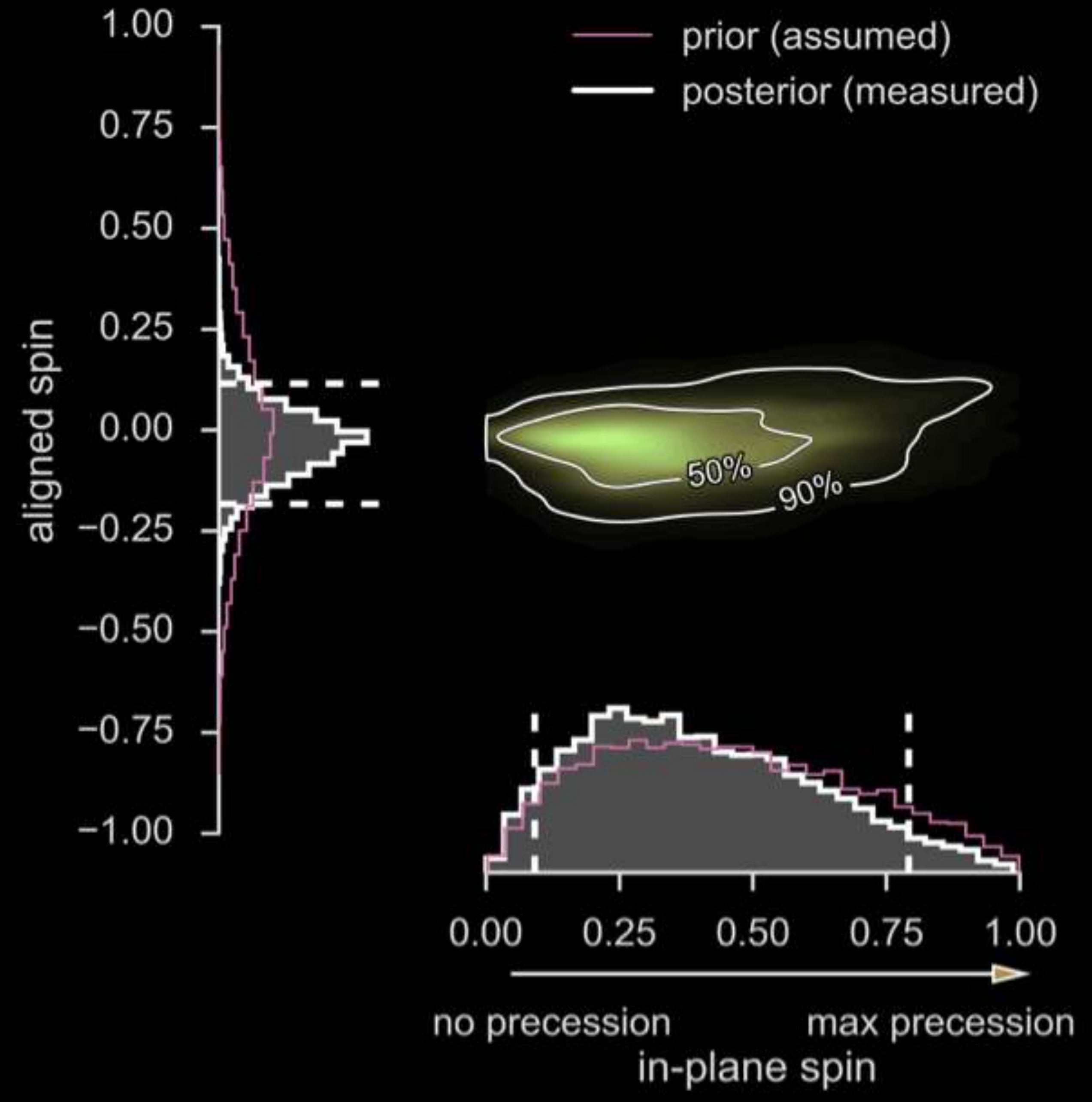


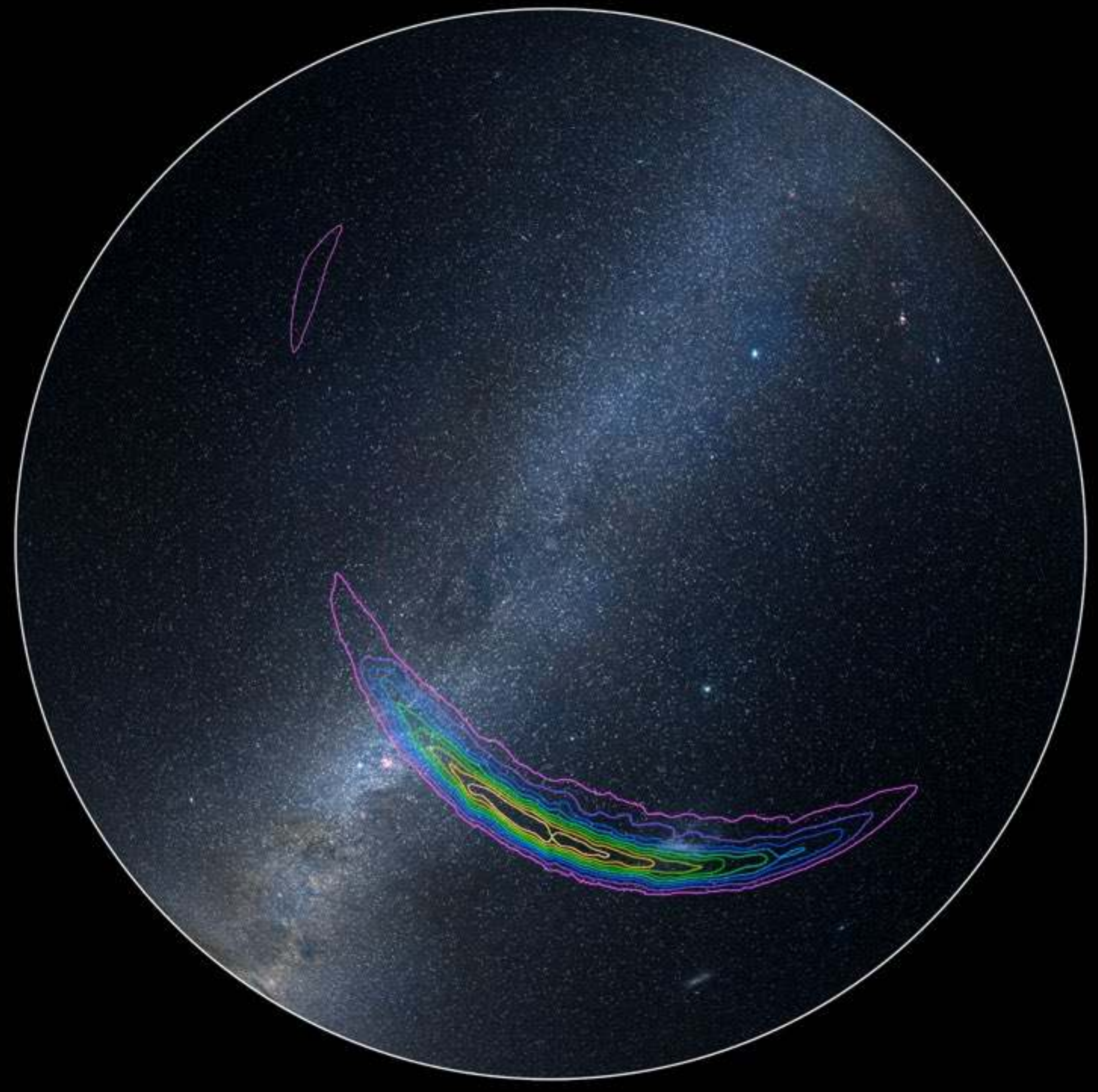
Video credit: LIGO


-0.76s

GW150914







distance ~400 Mpc

total initial mass ~63 $M_\odot$

total final mass ~60 $M_\odot$

maximum speed ~0.6 c

maximum power $\sim 3.6 \times 10^{56}$ erg s^{-1}

GW150914

what did we learn

gravitational waves exist!

consistent with general relativity

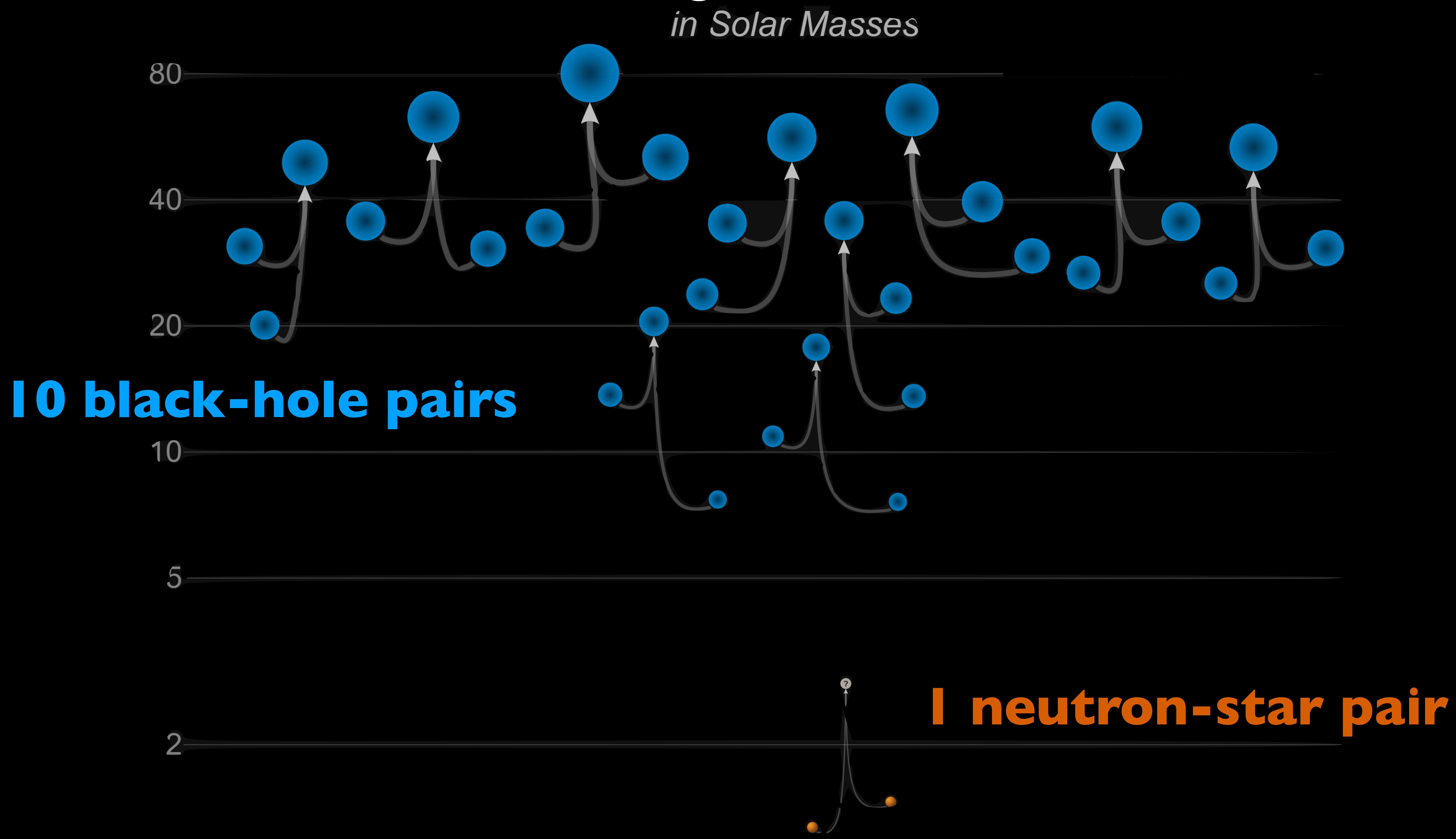
black-hole binaries exist

there exist heavy stellar-mass black holes

they don’t spin too fast

…

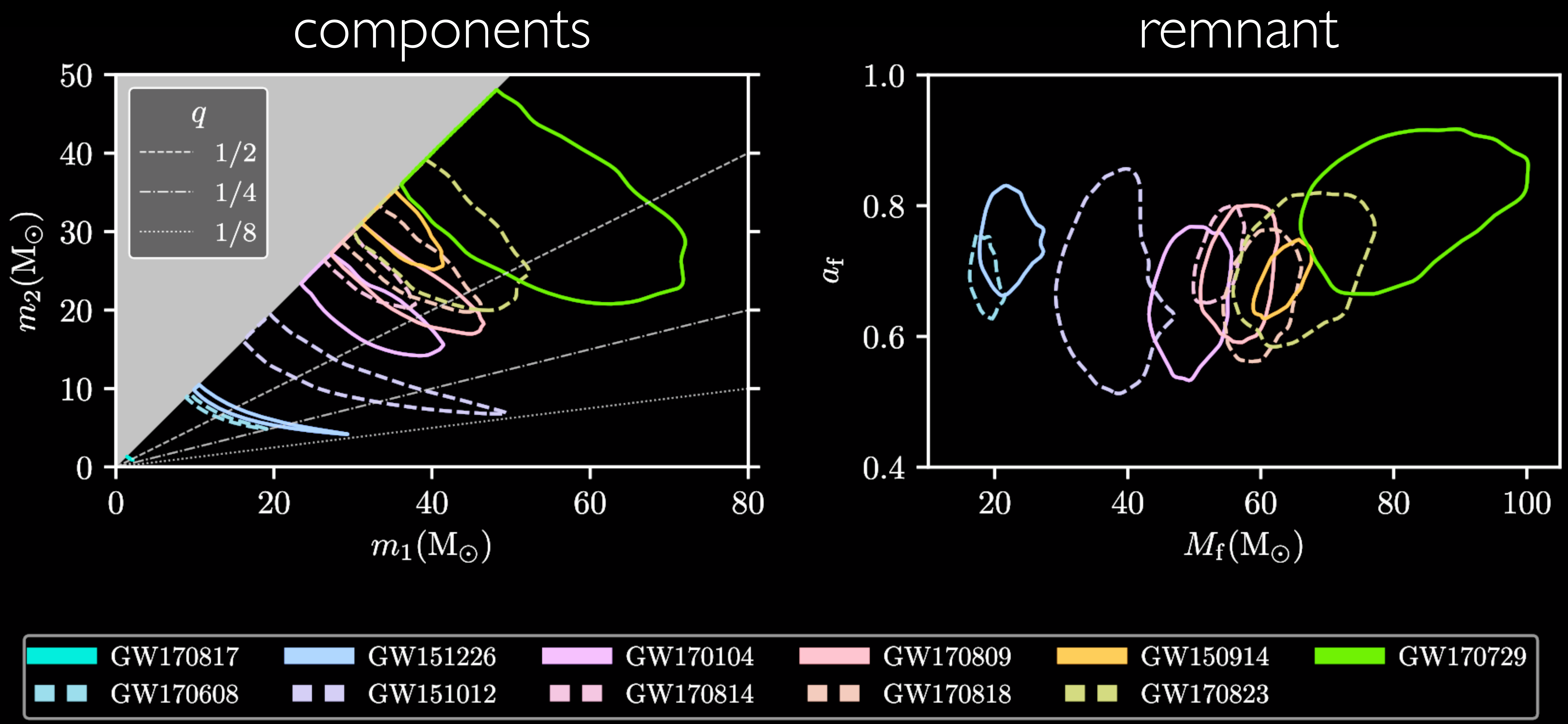
LIGO and Virgo detections to date



GWTC-1 detection catalog [arXiv:1811.12907]

Image credit: LIGO/Virgo/F. Elavsky/Northwestern

masses and spins

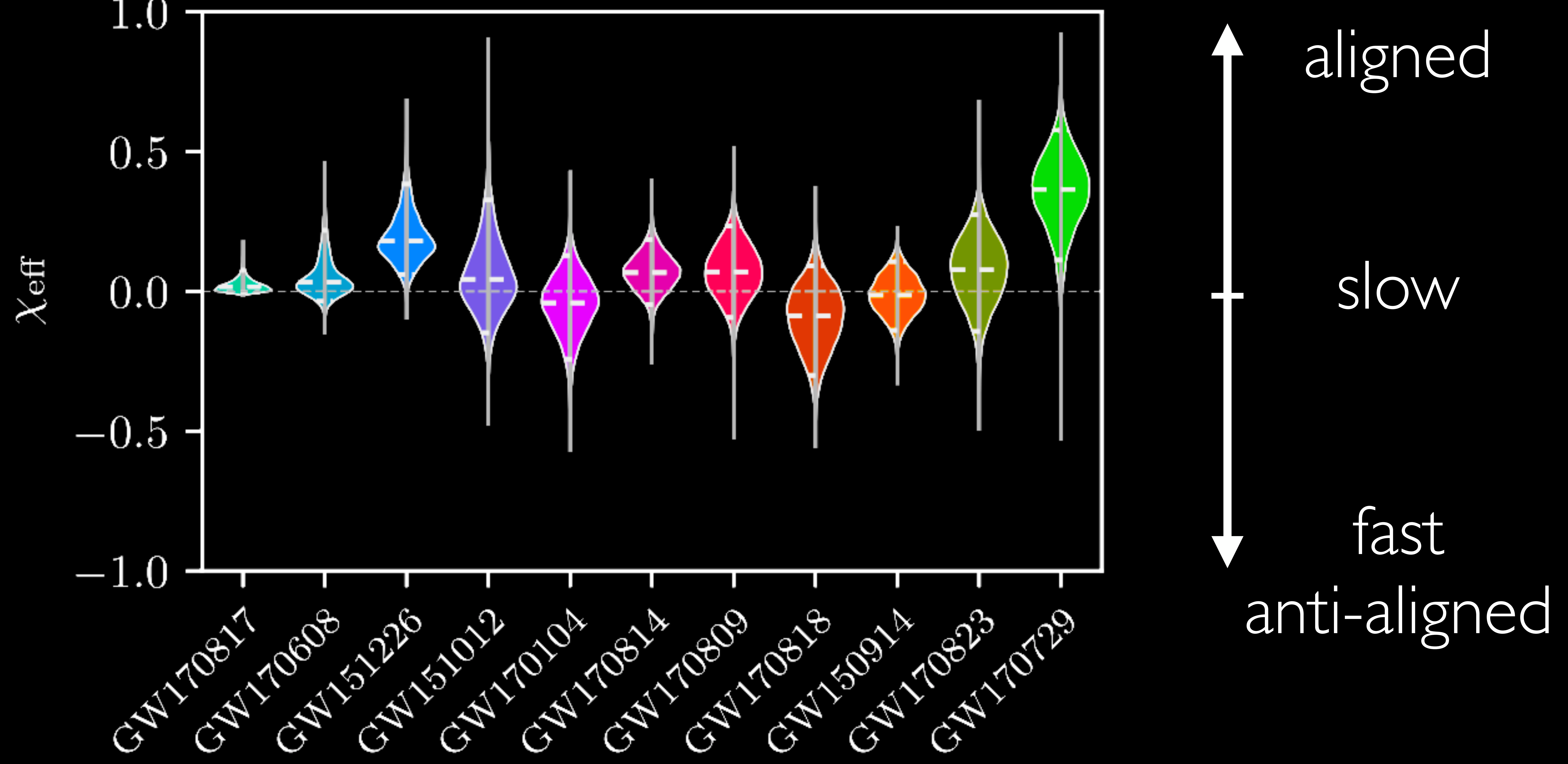


(contours indicate 90%-credible region)

[arXiv:1811.12907]

masses and spins

component spins

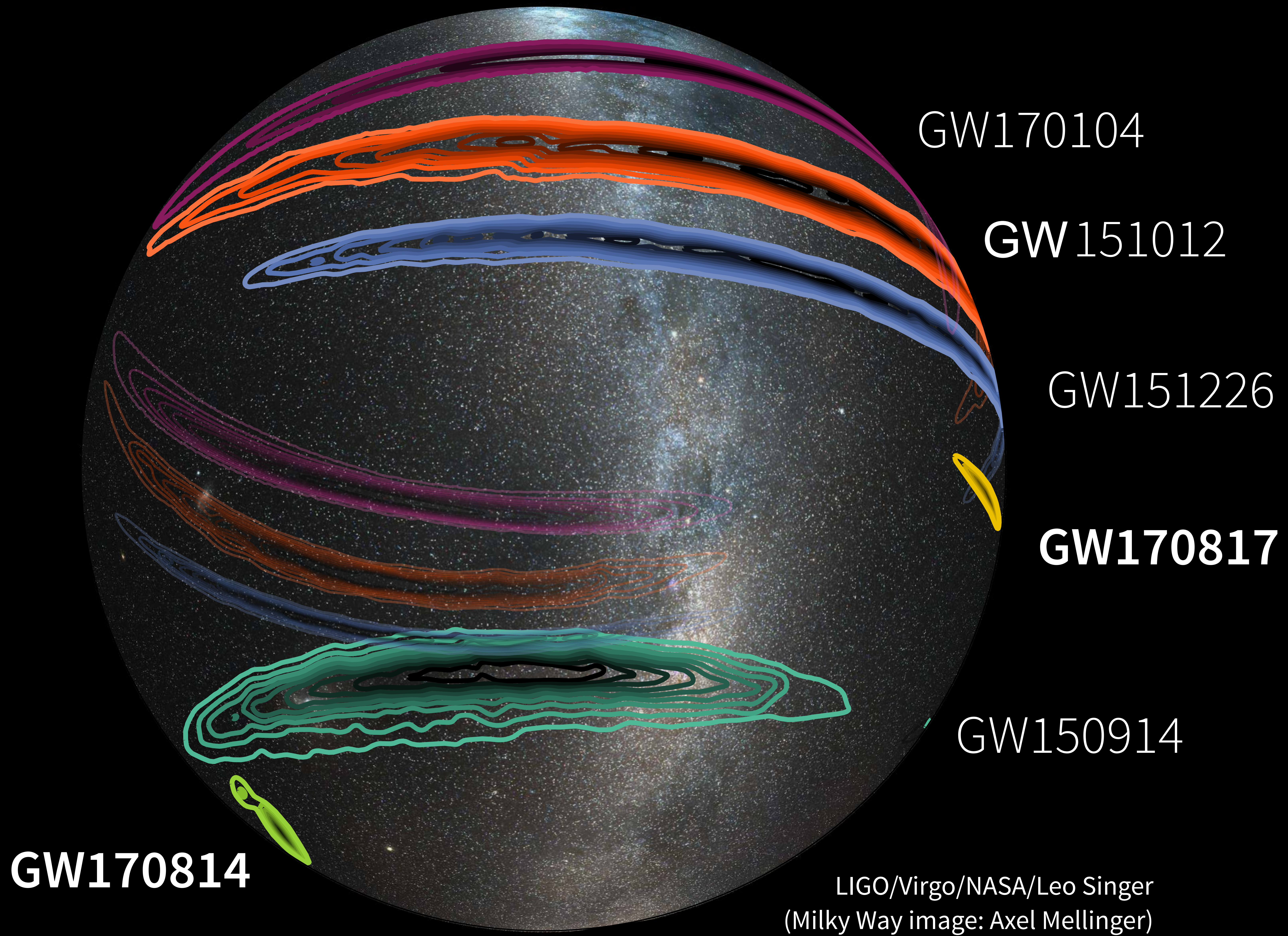


(violin plots summarize 1D posteriors on effective spin; "aligned" refers to orbital angular momentum)

[arXiv:1811.12907]

Video credit: NASA Goddard

sky localization

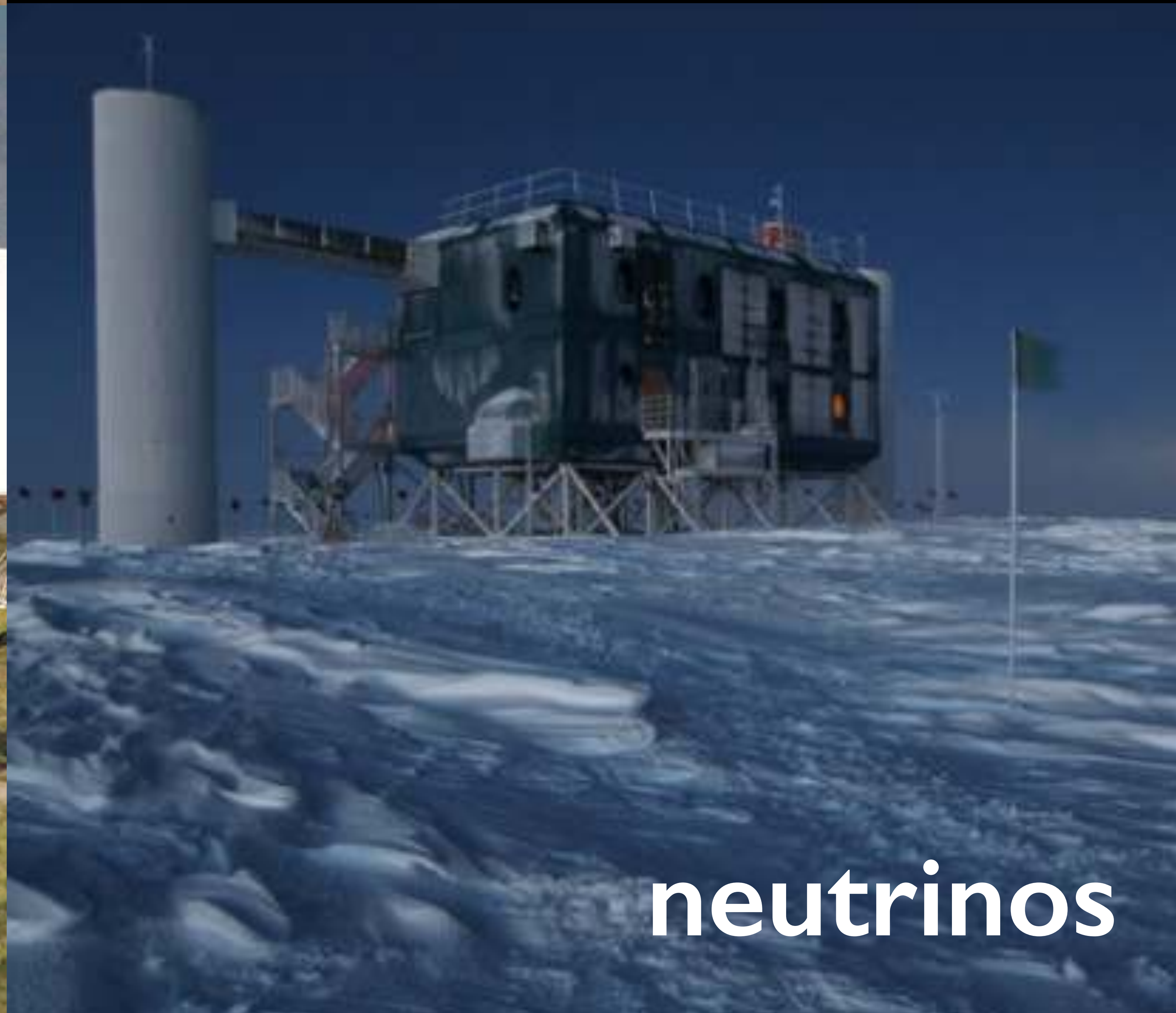


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

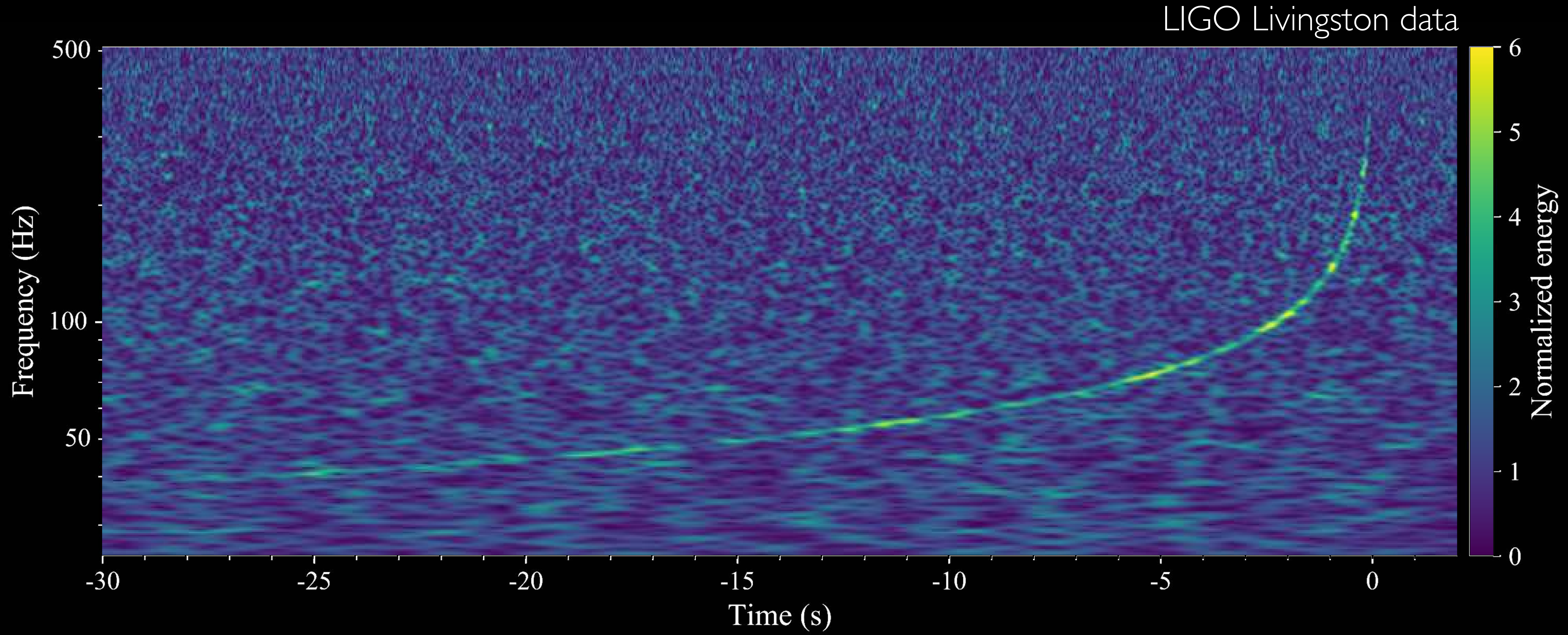
multimessenger astronomy

agreements with 95 observatories

~200 EM instruments



GW170817



Credit: LIGO Virgo

GW170817

what did we learn

NS mergers cause (short) γ-ray bursts

first direct limits on the speed of GWs

tests of equivalence principle

Hubble constant measurement

constraints on NS equation of state

…

some of the

scientific potential of GWs

studying **stellar and galaxy evolution**

testing **general relativity**

understanding the nature of **black-holes**
(or their mimickers)

resolving tensions in **cosmology**

learning about **nuclear matter**

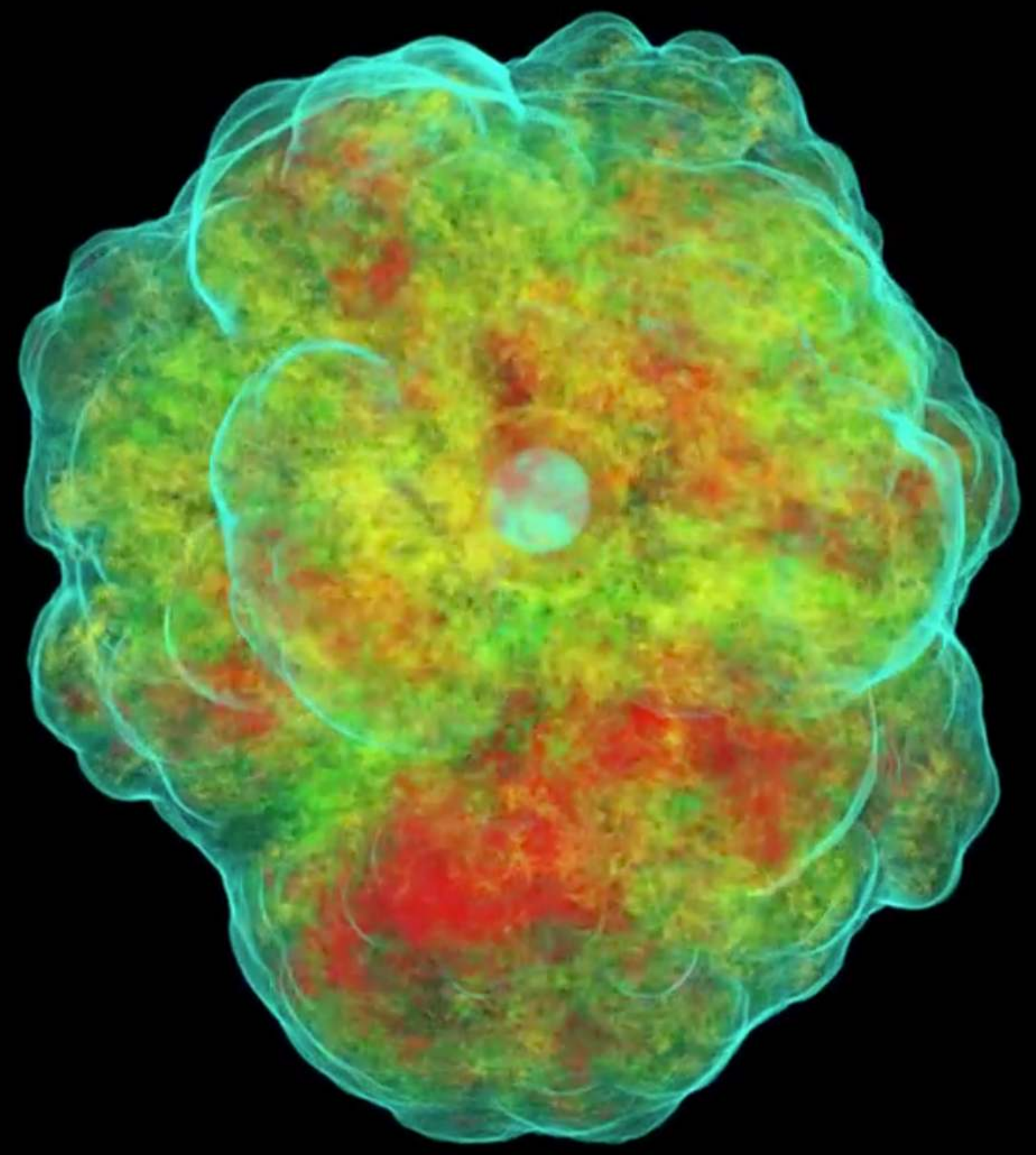
probing **dark matter**

…

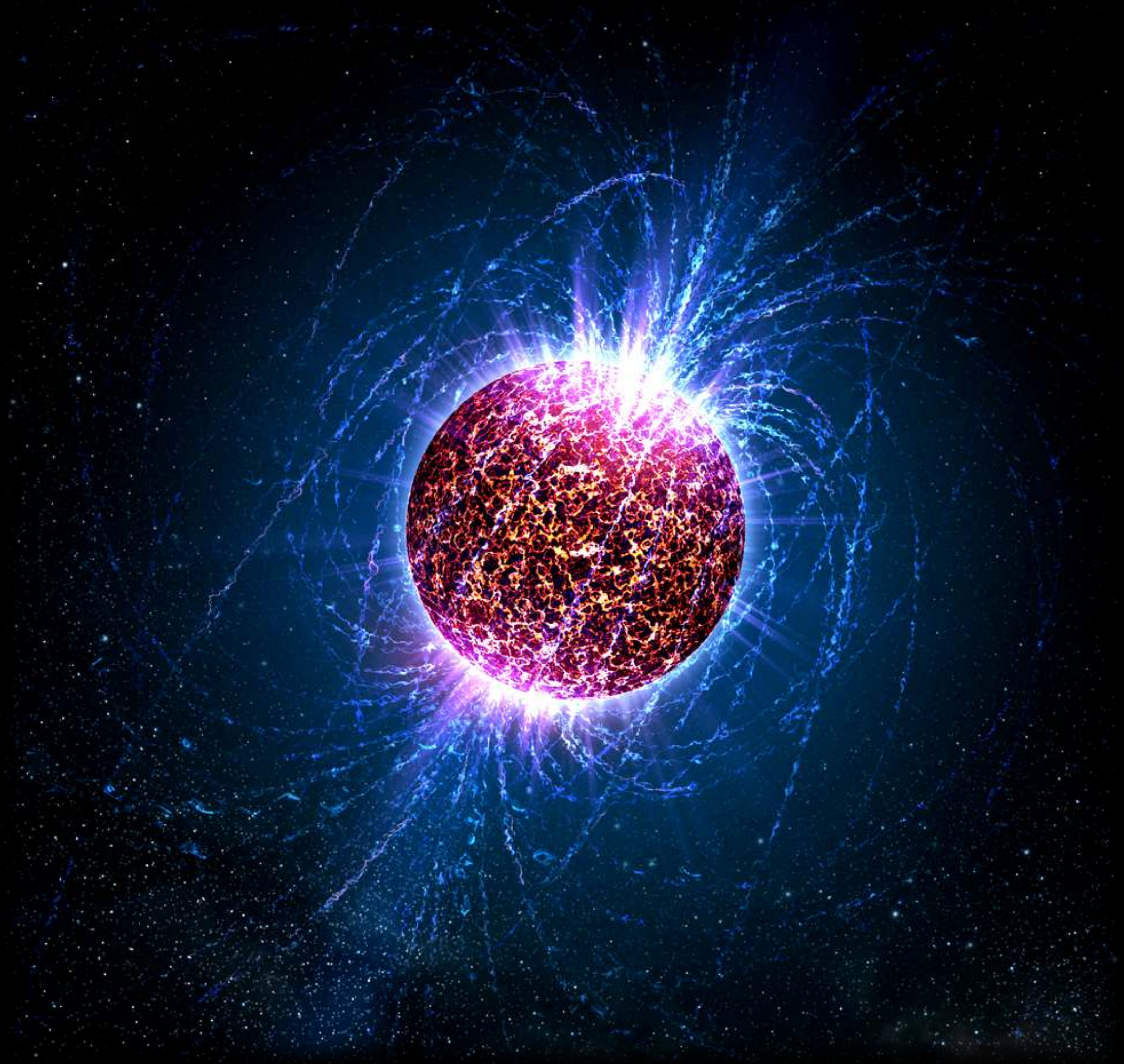
PART III
the future

more sources!

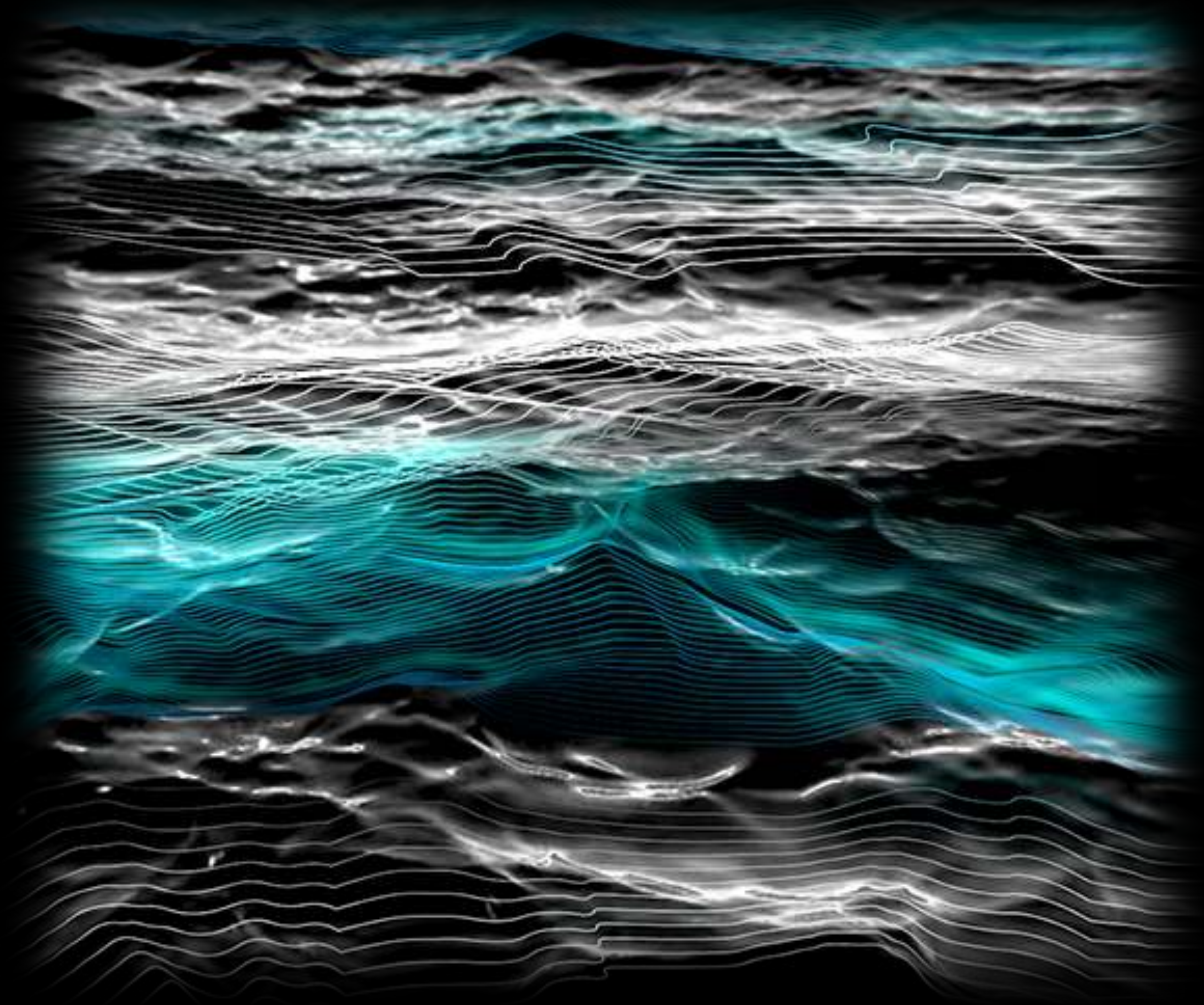
there's more out there than BH and NS mergers



supernovae



pulsars

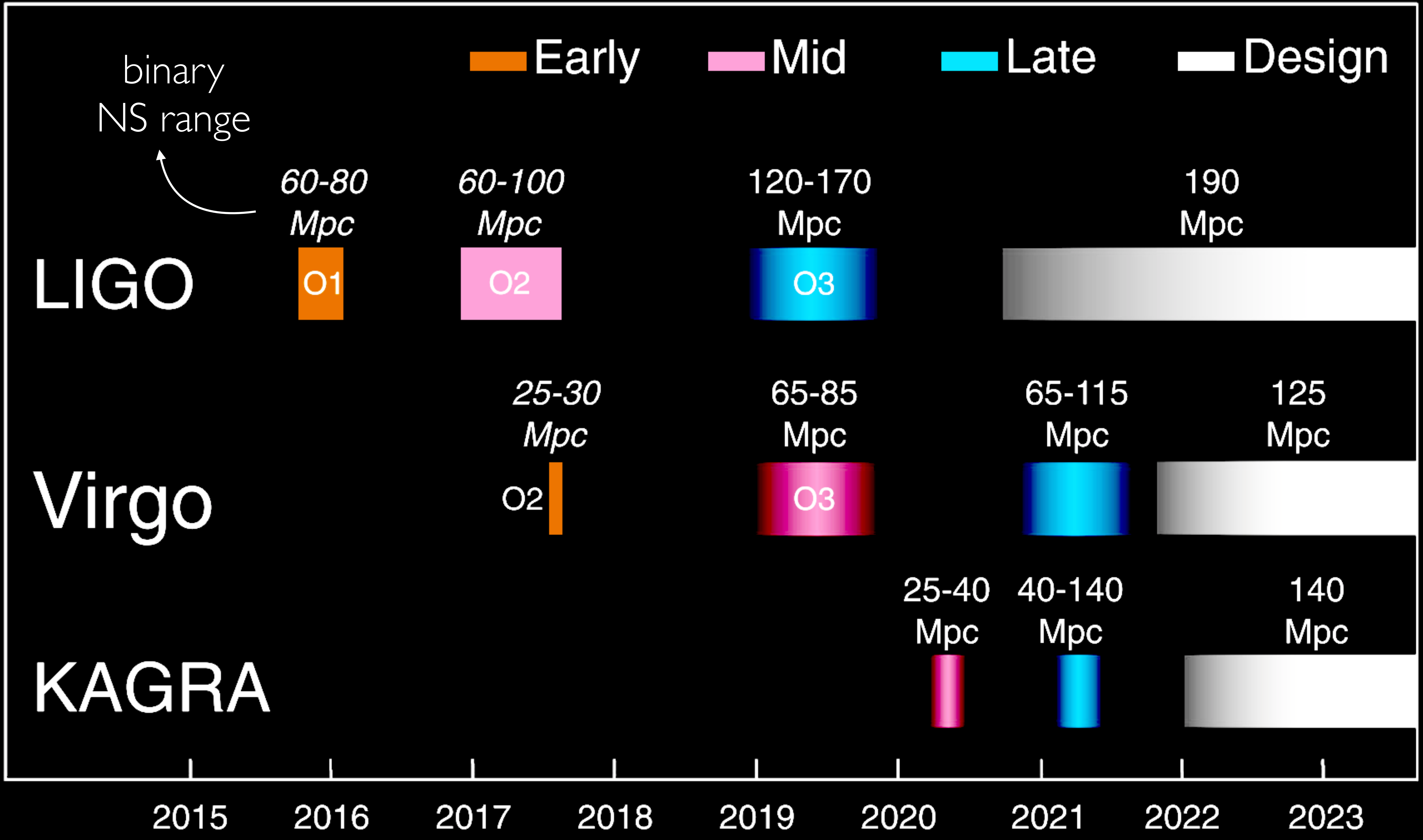


stochastic background

and perhaps something more exotic? expect Nature to surprise us!

Credit: C. Ott / C. Reed / OzGrav

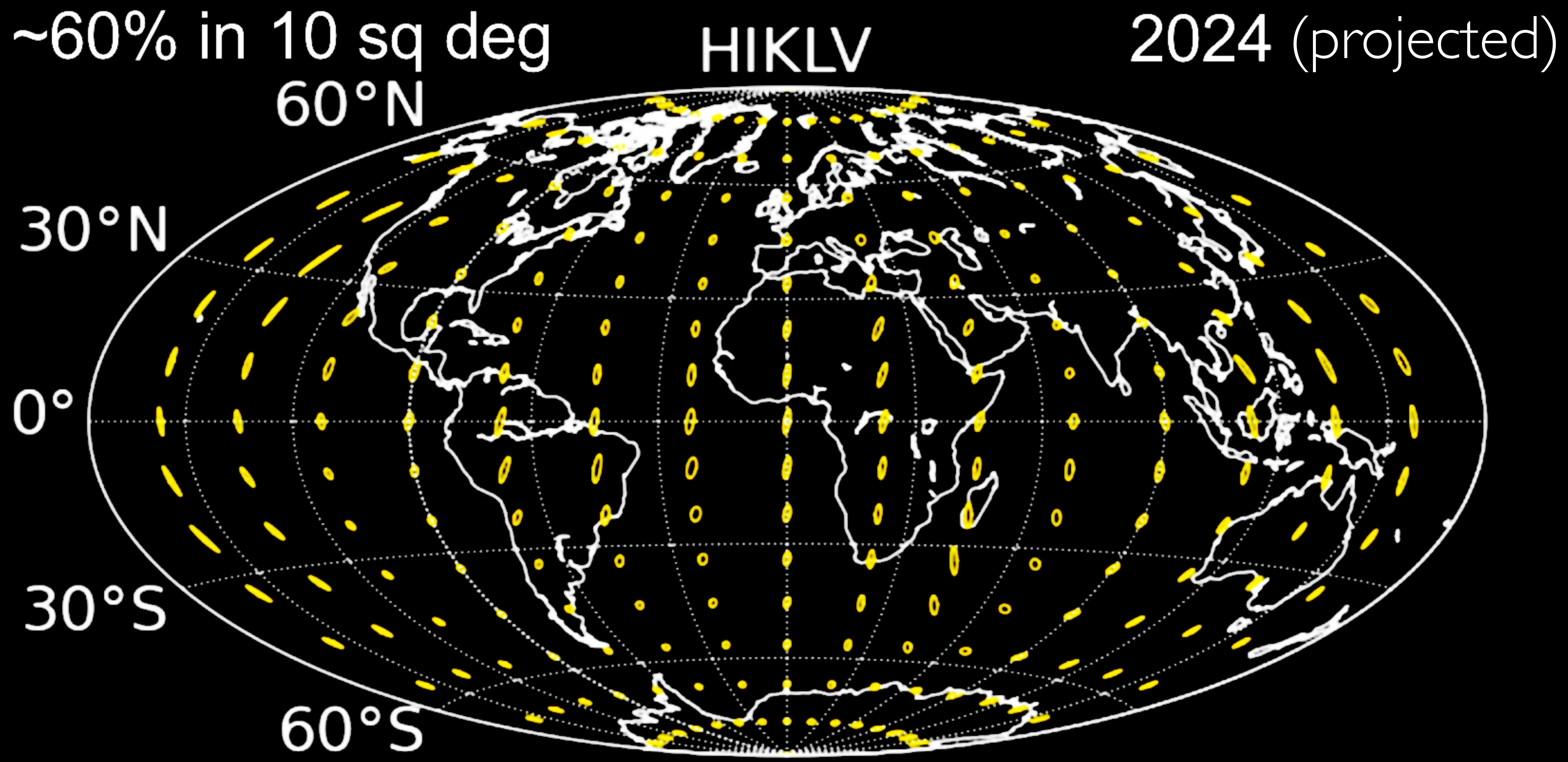
observation timeline



Abbott et al. doi:10.1007/s41114-018-0012-9

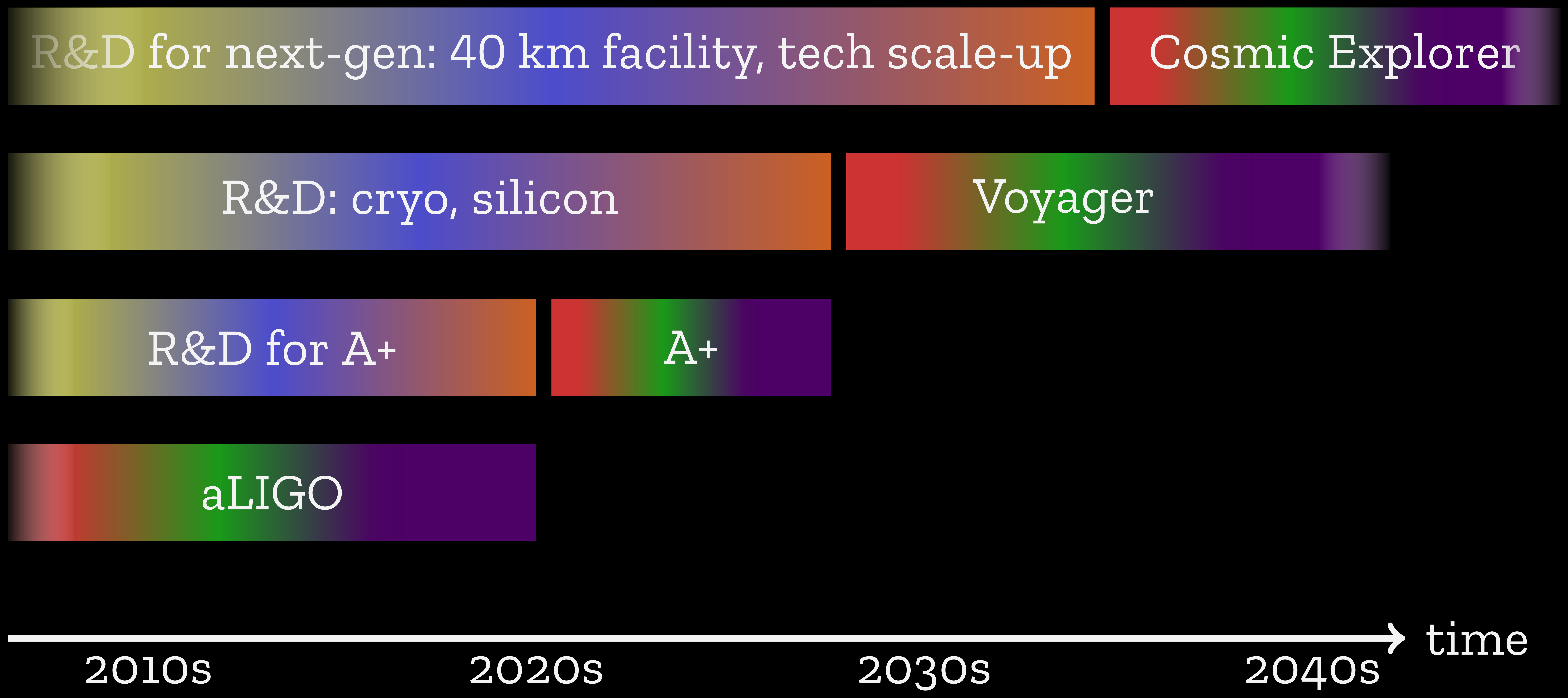
sky location to improve

LIGO + Virgo + LIGO India + KAGRA



Abbott et al. doi:10.1007/s41114-018-0012-9

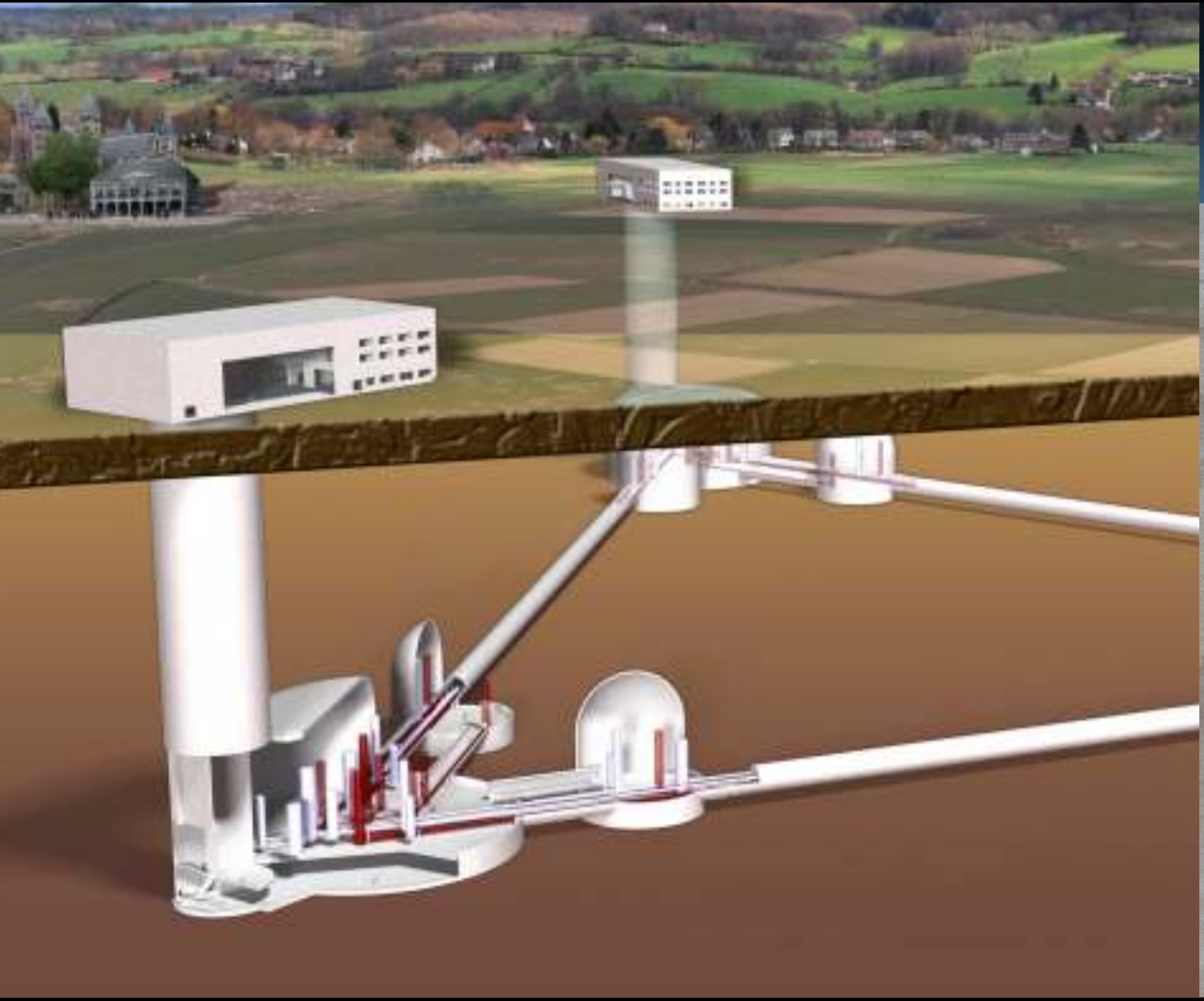
future US detectors

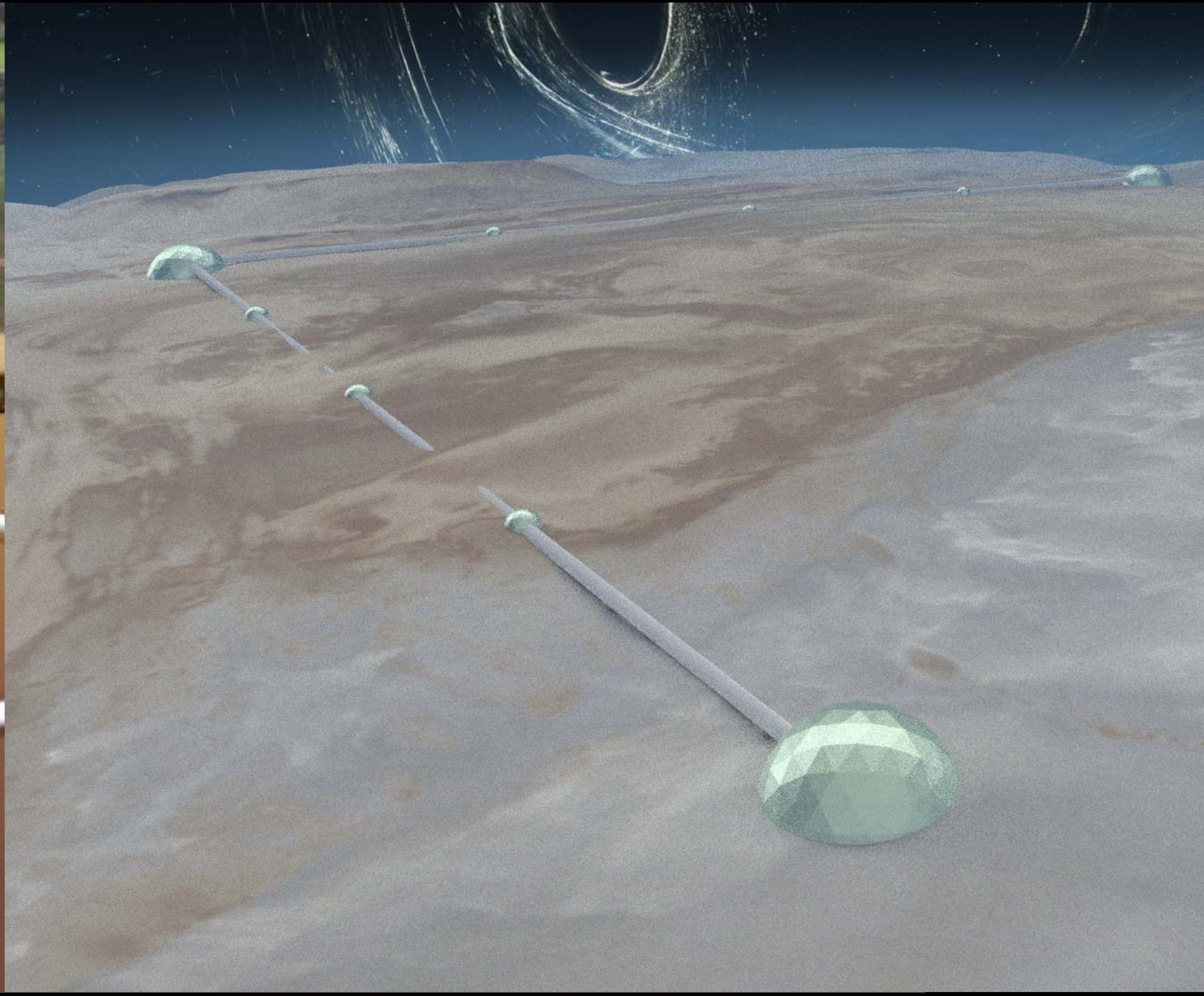


*possible timeline

Credit: Evan Hall

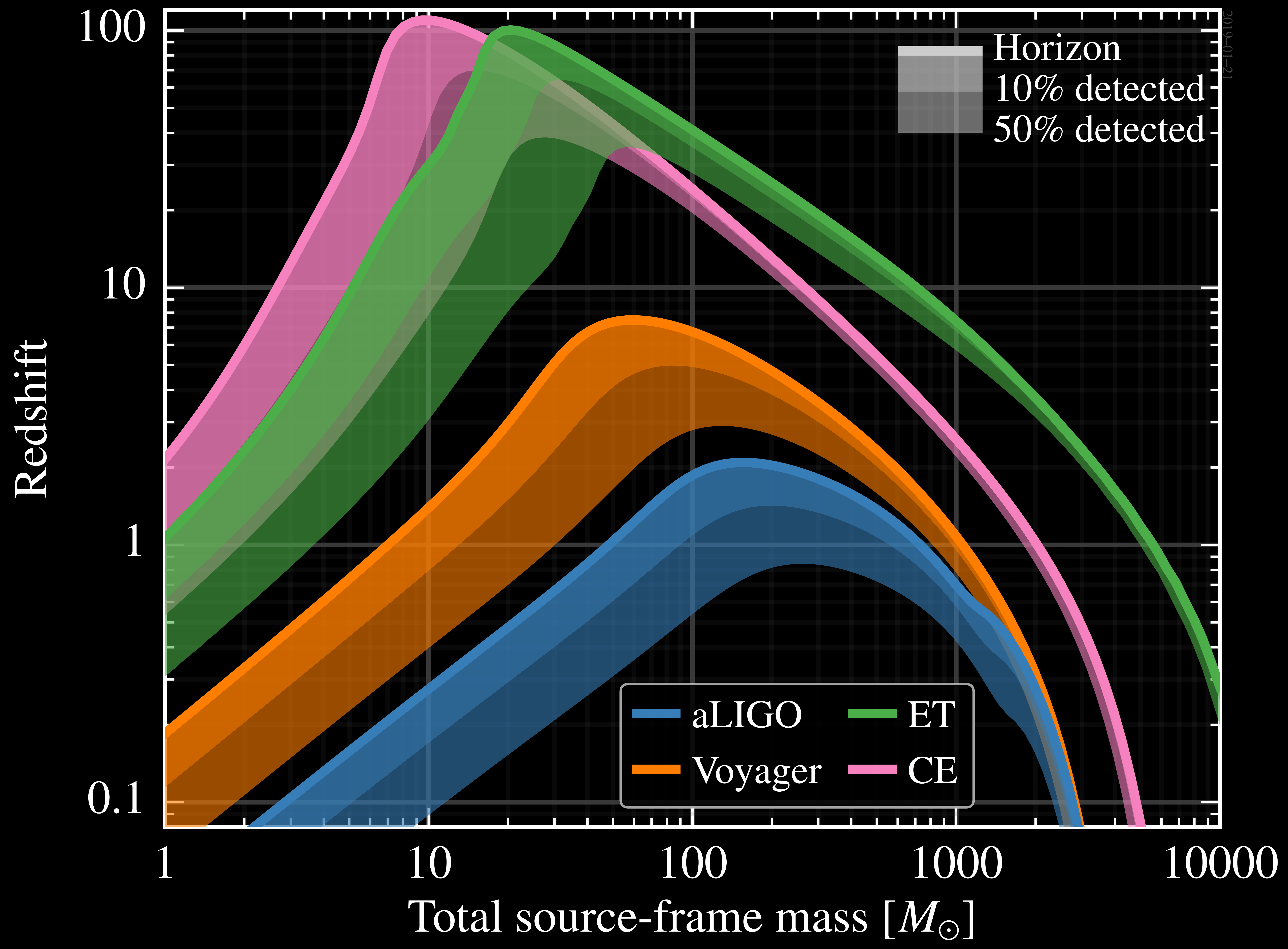
3G concepts





Einstein Telescope (EU) **Cosmic Explorer (US)**

BBH horizons

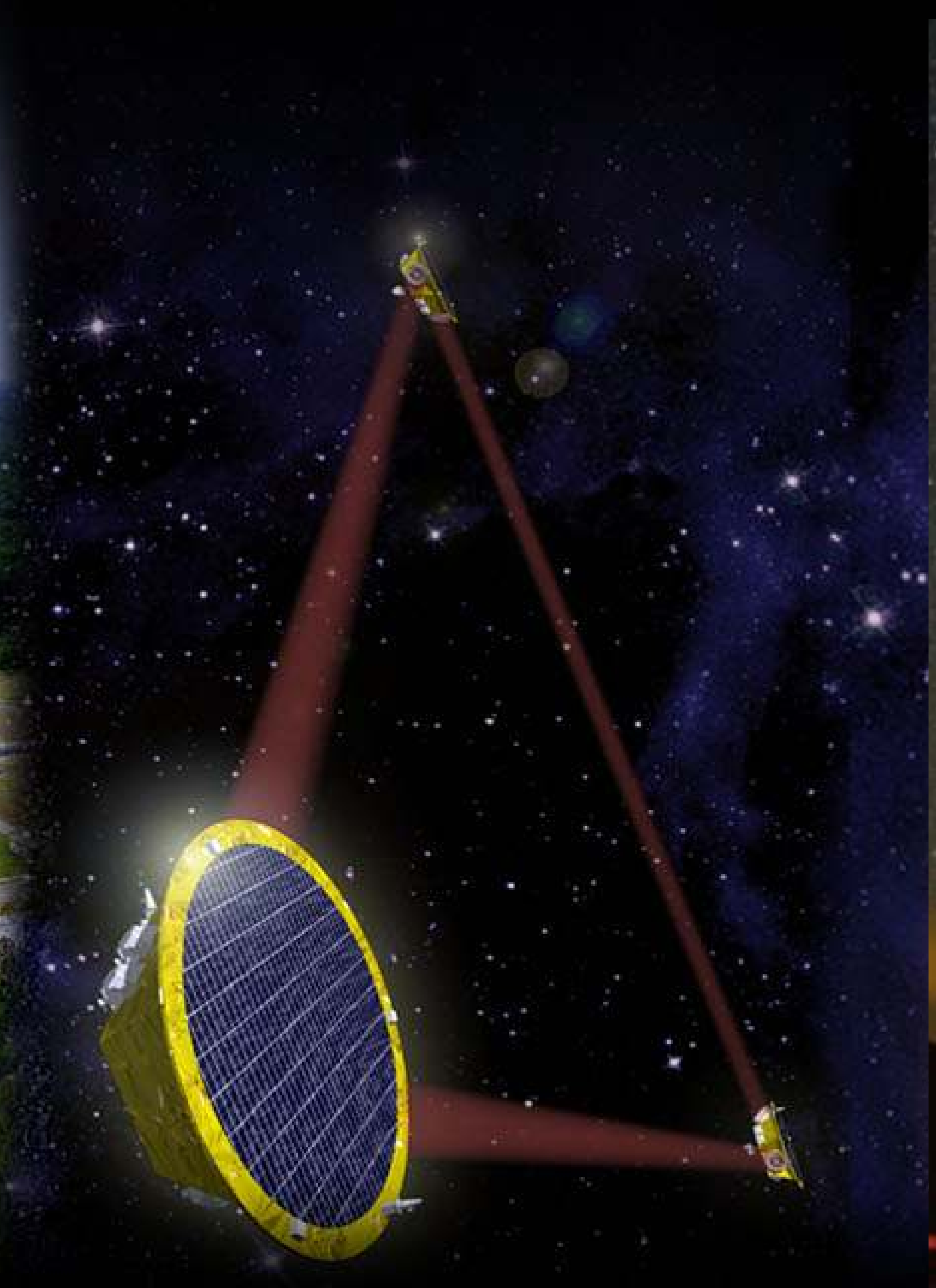


Credit: Evan Hall

Gravitational Wave Periods

Milliseconds

Minutes
to Hours



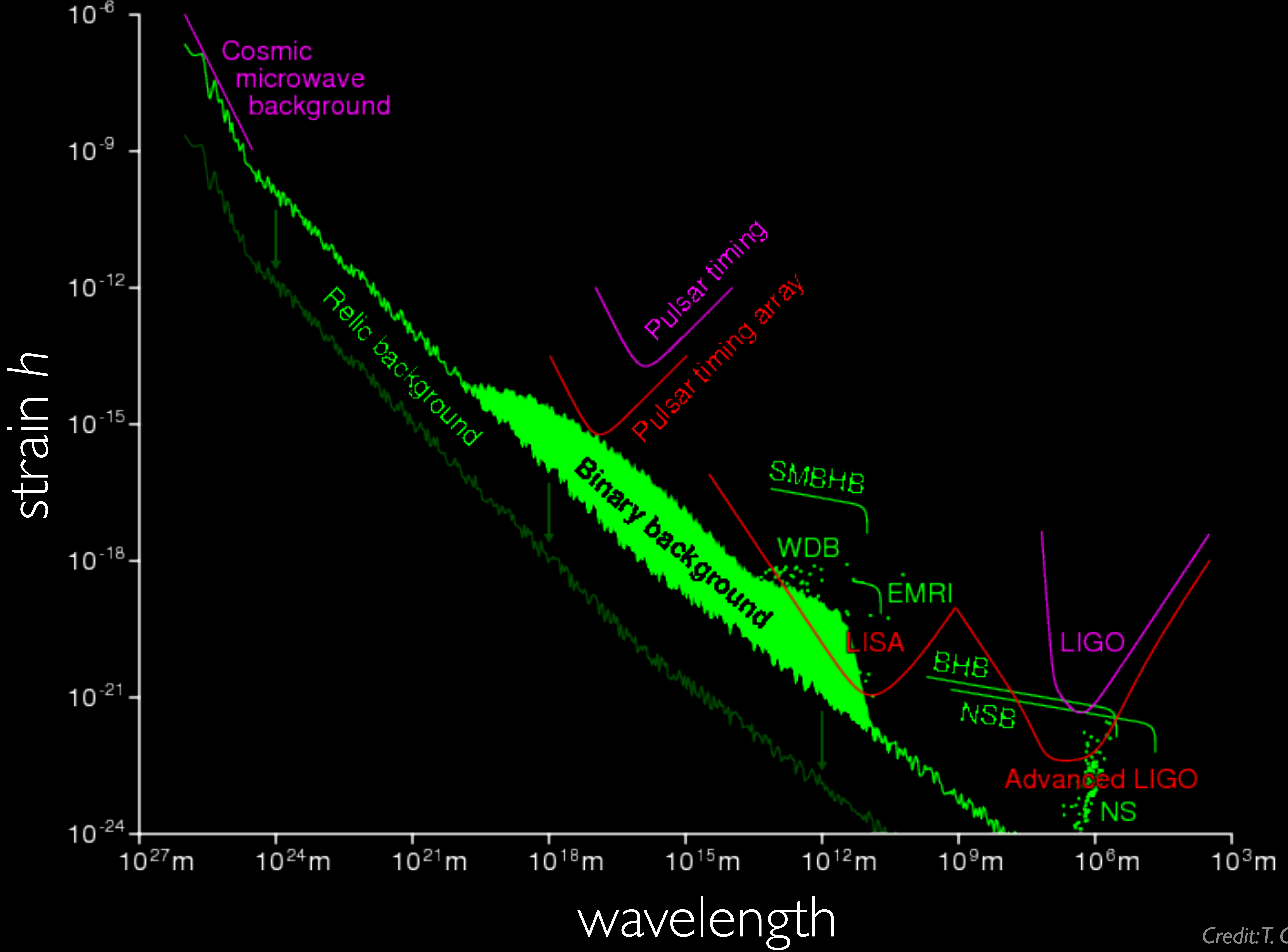
Years
to Decades

Billions
of Years

Credit: LIGO Virgo / J. Key

the GW spectrum

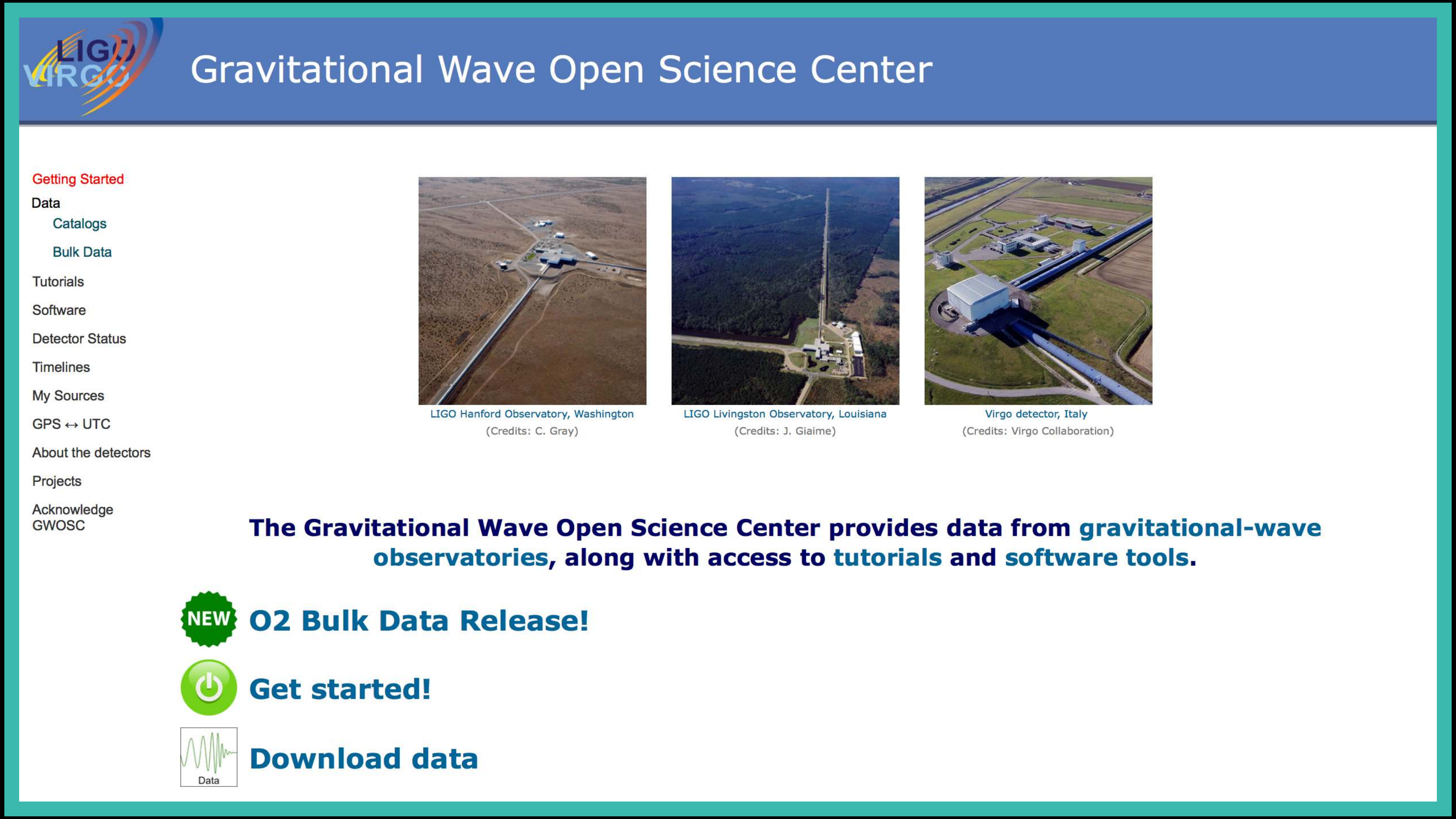
detectors and sources



Credit: T. Creighton

this is just the beginning!

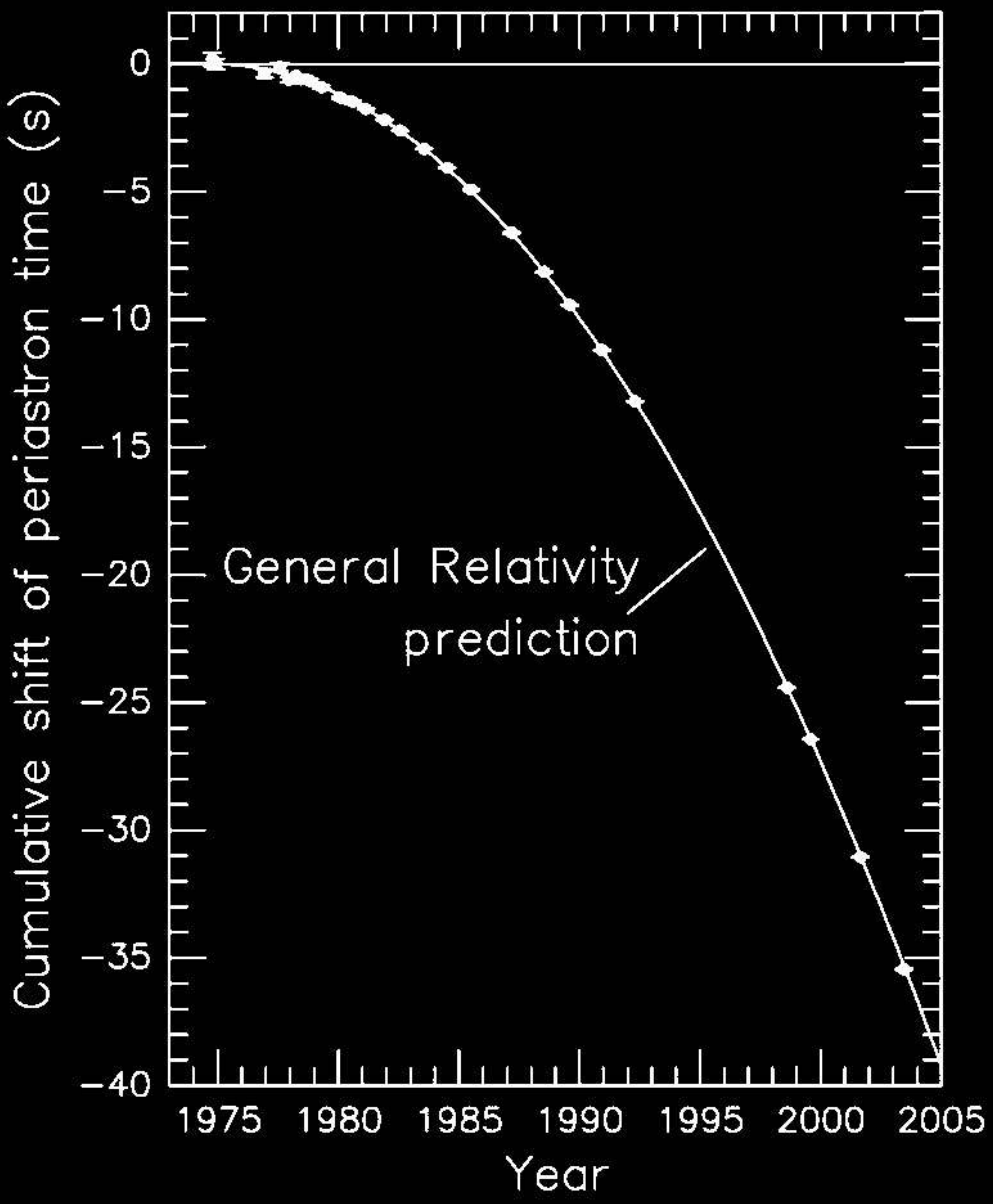
our data are public!

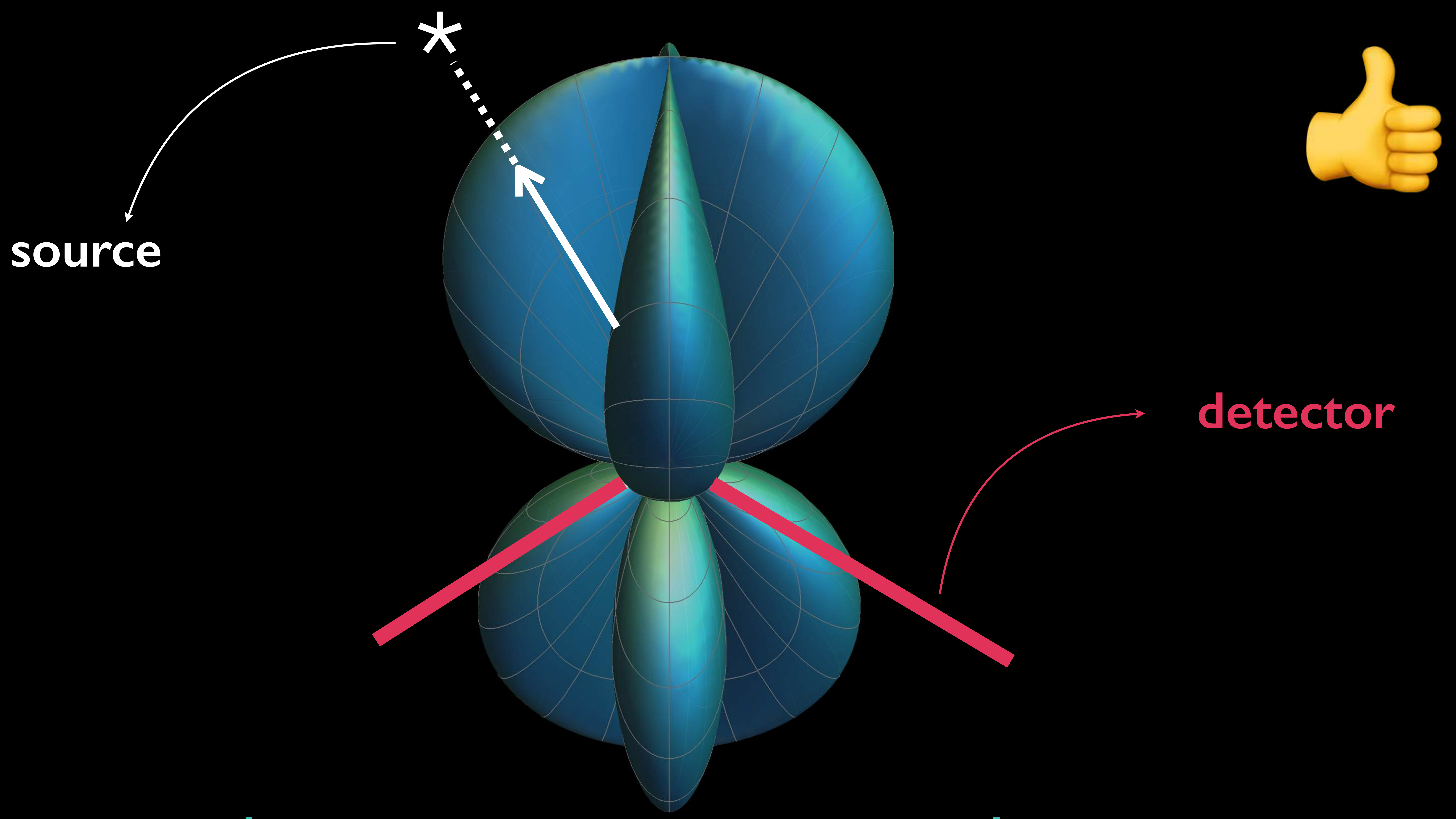


gw-openscience.org

LIGO was constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation and operates under cooperative agreement PHY-0757058 extra

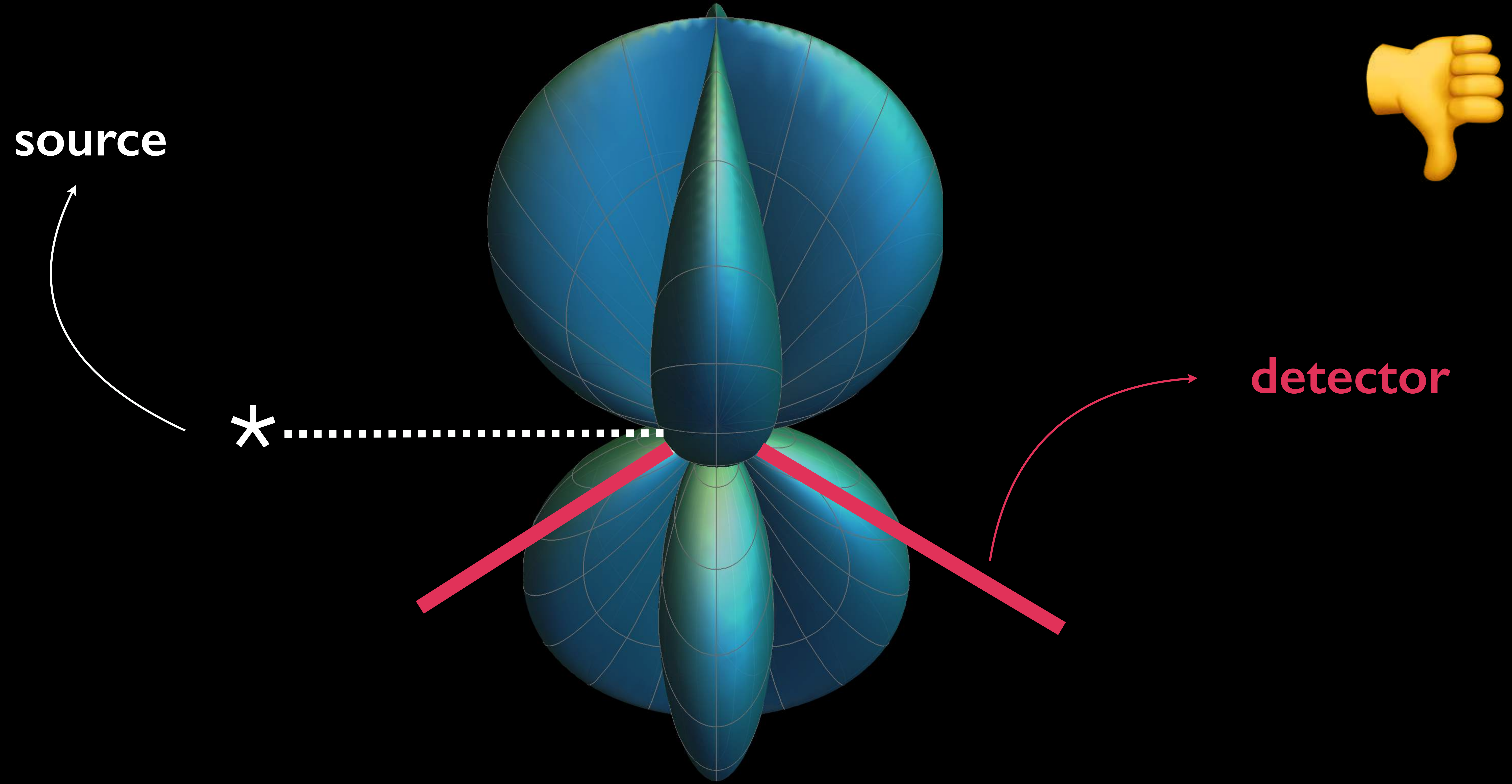
Hulse-Taylor pulsar





angular sensitivity to cross polarization

radial distance gives sensitivity to a wave from that direction; detector arms along *x* & *y* axis (straight lines)



angular sensitivity to cross polarization

radial distance gives sensitivity to a wave from that direction; detector arms along x & y axis (straight lines)

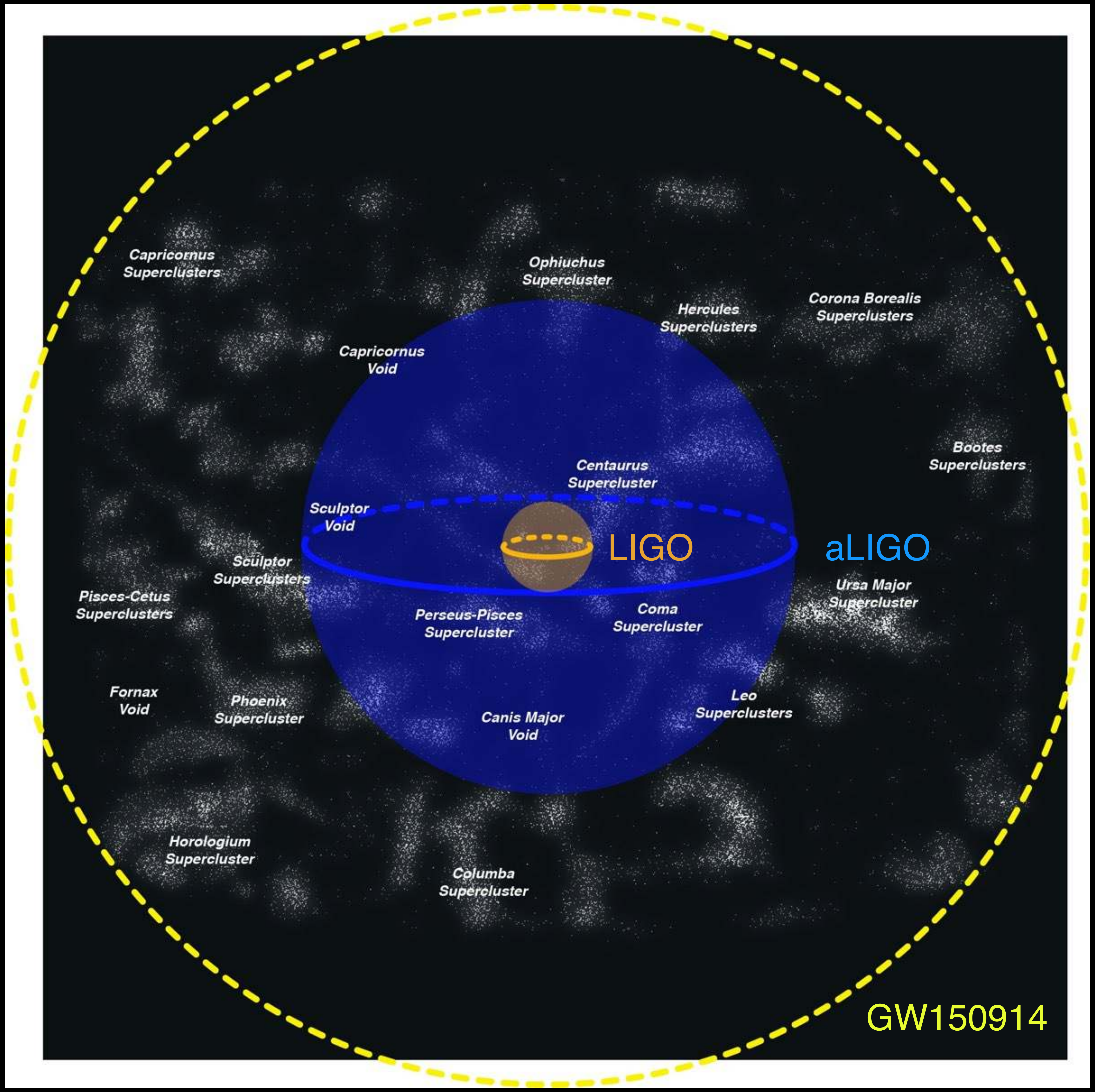


Image credit: LIGO / S. Larson

Near-term upgrades: A+ and AdVirgo+

~5 year time scale

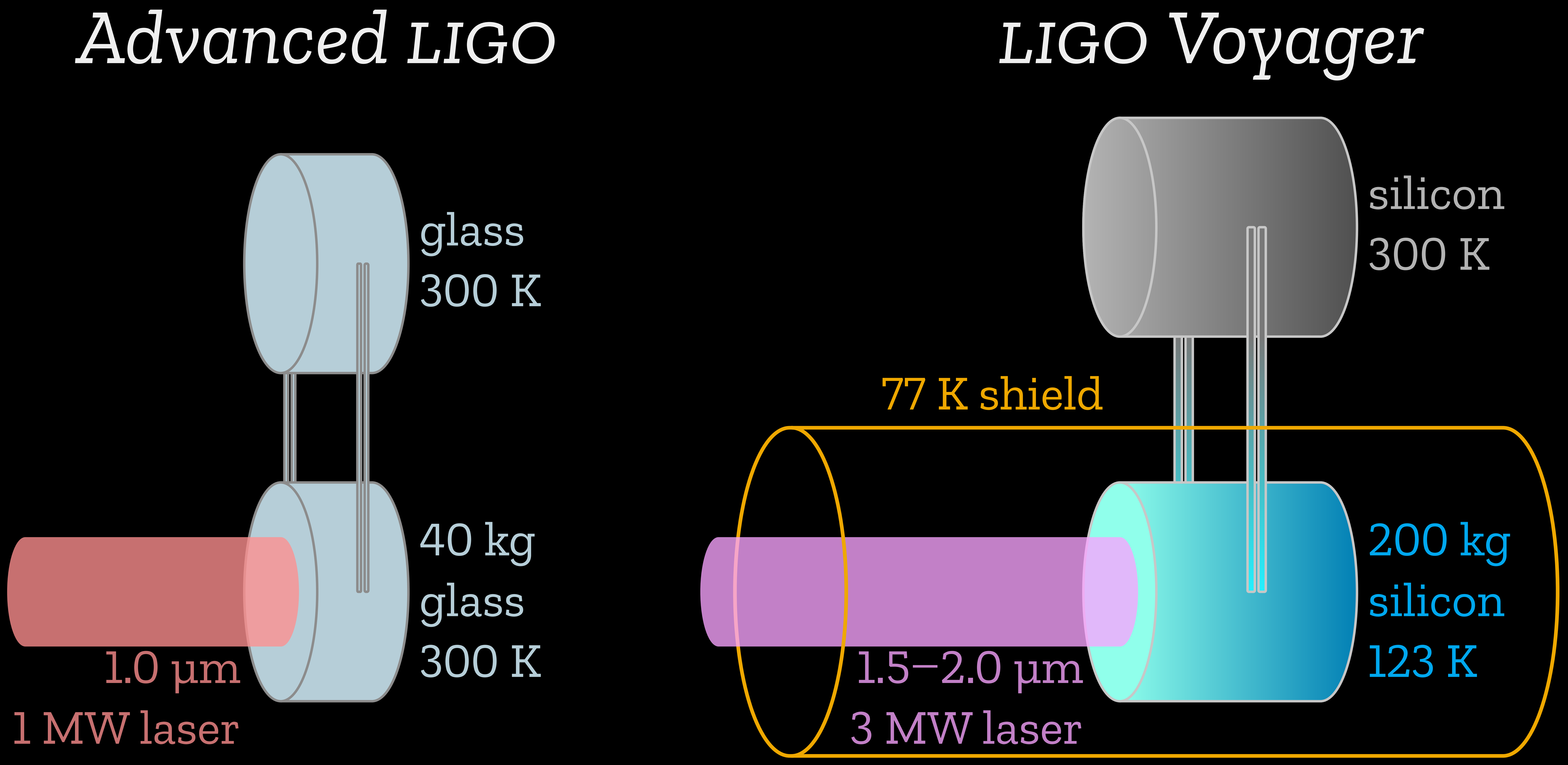
Modest upgrades to aLIGO and AdVirgo:

- Heavier test masses *(AdVirgo+ only)*
- Better mirror coatings
- Suspension modifications *(AdVirgo+ only)*
- Frequency-dependent squeezing
- Newtonian noise subtraction (*AdVirgo+ only*)

~1.7 strain improvement ⇒ ~5 rate improvement for A+

Courtesy: *Evan Hall*

Voyager: a next-gen detector in the LIGO facilities



N. Smith et al., *Cold voyage*, tech. rep. G1500312 (LIGO, 2015)

Courtesy: Evan Hall

Einstein Telescope (2)

Facility:

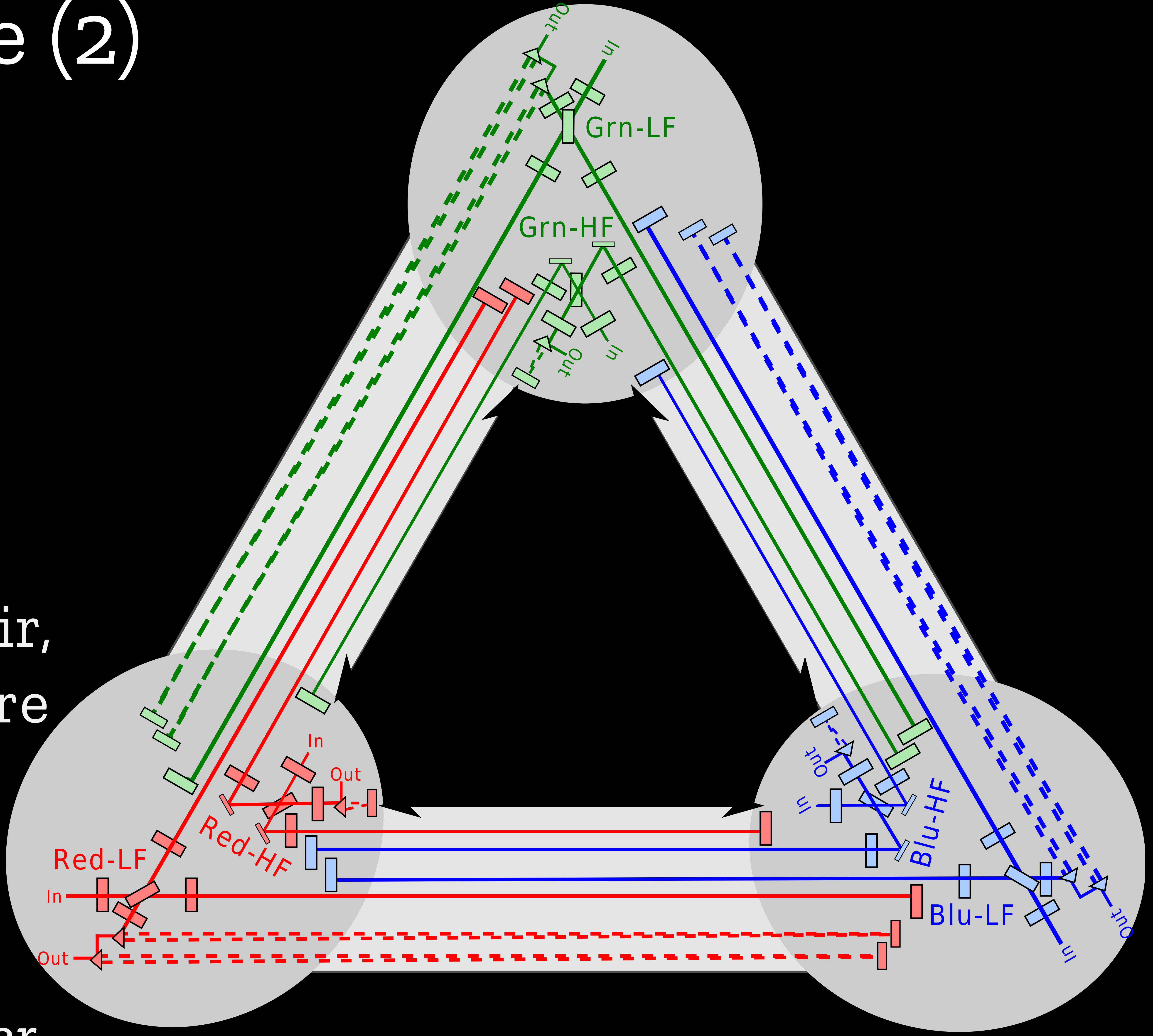
10-km triangle to be placed underground in Europe

Instrument:

Three pairs of detectors: in each pair, one room temperature and one cryogenic

Network:

Get good scientific output *even if no other next-generation facility is built*



Courtesy: Evan Hall

Cosmic Explorer (2)

Facility:

- A 40 km L-shaped facility to be placed either on the Earth's surface or underground

Instrument:

- One Michelson interferometer to achieve design sensitivity
- If Voyager technology is mature: use cryogenic silicon
- Otherwise: fall back to aLIGO technology (with a slight sensitivity penalty)

Network:

- *Not* a stand-alone instrument: intended to operate as part of a global network

Courtesy: Evan Hall